

# Lead-bismuth cooled reactors: history and the potential of development. Part 1. History of development\*

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## Abstract

The article is devoted to the history of the creation of lead-bismuth-cooled reactor units (RUs) for nuclear-powered submarines (NPSs), which were developed in the absence of the necessary knowledge and experience, as well as under strict deadlines for completing work, which practically excluded the possibility of carrying out related full-scale scientific research. This led to a number of failures at the stage of developing this unique technology, the causes of which were later identified and eliminated. The authors explain the reasons for choosing a lead-bismuth eutectic alloy as a coolant, outline the main scientific and technical problems solved in the course of developing a lead-bismuth-cooled reactor unit, including those related to the coolant and corrosion resistance of steels, consider issues of ensuring radiation safety during work related to the release of polonium, ensuring the reliability of steam generators, incidents and accidents that occurred during the period of operation and ways to eliminate their causes.

## Keywords

Lead-bismuth coolant (LBC), nuclear-powered submarine (NPS), reactor, steam generator, polonium, accident, corrosion, operating experience, core

## Introduction

On June 26, 1954, the world's first nuclear power plant was put into commercial operation in Obninsk, which marked the beginning of the development of nuclear power engineering. This fact is well known throughout the world. It is much less known, however, that just four years later, on December 25, 1958, in Obninsk, specialists of the Institute of Physics and Power Engineering carried out a physical start-up of the world's first lead-bismuth-

cooled reactor at the 27/VT facility. It was a ground-based prototype nuclear power unit (NPU) of the first pilot nuclear-powered submarine K-27 of the Soviet Navy's Project 645, with two lead-bismuth reactors. The developers of the reactor plant were: IPPE (scientific supervisor) and OKB Gidropress (chief designer).

The LBC of the eutectic composition had been chosen by A.I. Leipunsky (Leipunsky 1990) for nuclear breeder reactors even before the work on NPSs were deployed in the USSR on a scheduled basis in August 1952 after the

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issuance of the relevant Decree of the Council of Ministers. Later, however, Leipunsky reoriented work on fast reactors (FRs) to the sodium coolant, since the LBC, having worse thermal-physical properties, could not provide a short plutonium doubling time, which was an indispensable requirement in those years.

The nuclear power units for nuclear-powered submarines were carried out both in the Soviet Union and in the United States in two directions: (1) pressurized water reactors and (2) liquid-metal-cooled reactors. In contrast to the United States, where sodium, which did not justify itself in the operating conditions of NPUs of NPSs, was chosen as the LMC, lead-bismuth-cooled reactors, after a number of failures, were mastered and successfully operated on serial NPSs of Projects 705 and 705K (Gromov et al. 1999). Based on the critically considered experience in designing and operating nuclear-powered submarine reactors, the development of a small modular fast reactor (SVBR-100) for civilian purposes is currently underway, which meets the requirements for Generation IV reactors.

A.I. Leipunsky proposed and substantiated the lead-bismuth eutectic alloy as a coolant for nuclear-powered submarine reactors, despite its worse thermal-physical properties as compared to those of sodium. The LBC was the basis for developing and constructing (in addition to the 27/VT facility) the first pilot NPS of Project 645 equipped with two reactors and the nuclear submarine of Project 705K (BM-40/A) with reactor units developed by OKB Gidropress (Podolsk); as well as the reactor unit of the KM-1 facility and the NPS of Project 705 (OK-550) with reactor units developed by OKBM (Nizhny

Novgorod). As a result, eight NPSs with lead-bismuth-cooled reactors were built, of which seven were single-reactor Alfa-class ones (according to NATO classification), and two ground-based prototype facilities. In total, 15 cores were operated, the total operating time of which in all modes was about 80 reactor-years. For its speed and maneuverability, the Project 705 NPS was listed in the Guinness Book of Records (it could successfully evade American torpedoes).

The lead-bismuth-cooled reactor units were developed in the absence of the necessary knowledge and experience, and under strict deadlines for completing the work, which practically excluded the possibility of carrying out related full-scale scientific research, which caused numerous failures at the stage of mastering this technology. Fig. 1 shows a photograph of A.I. Leipunsky with his 'first-call' followers.

## History of development of lead-bismuth-cooled reactors

### Reasons for choosing the lead-bismuth eutectic alloy as a coolant

The feasibility of using the lead-bismuth eutectic alloy as a primary coolant is due to its physicochemical and thermodynamic properties, which make it possible to fully satisfy the requirements for nuclear-powered submarine reactors in terms of weight and size characteristics, maneuverability and safety.



**Figure 1.** A.I. Leipunsky and his followers. First row, left to right: V.Ya. Pushko, B.F. Gromov, A.I. Leipunsky, V.A. Kuznetsov, L.N. Usachev. Second row, left to right: A.I. Mogilner, G.I. Toshinsky, L.A. Chernov, Yu.A. Prokhorov, V.V. Chekunov.

A very high boiling point  $\sim 1670^\circ\text{C}$  makes it possible to:

- have a low pressure in the primary circuit, reduce the thickness of the walls of equipment and pipelines and not impose restrictions on the maneuverability of NPUs in terms of thermal cycling strength, as well as use steel as the material of the reactor pressure vessel that is not subject to radiation embrittlement under operating conditions, and ensure high maneuverability of nuclear submarines;
- eliminate the loss of coolant due to its boiling in case of the depressurization of the primary circuit and increase safety;
- eliminate the possibility of a heat transfer crisis and to increase the thermal engineering reliability of the core;
- have a higher (compared to pressurized water reactors) temperature of the coolant at the reactor outlet, significantly increase the temperature difference in the steam generator (SG) and ensure a higher compactness of the reactor plant, which is important when constructing nuclear submarines with limited displacement.

The possibility of obtaining superheated steam with increased (in comparison with pressurized water reactors) parameters, which made it possible to increase the thermodynamic cycle efficiency and the steam pressure in the turbine condenser, reduce its dimensions and vessel diameter as well as NPS displacement.

The chemical inertness of the coolant excluding exothermic reactions and hydrogen generation upon contact of the LBC with water and air, which is possible in emergency situations, which ensures explosion and fire safety in case of the depressurization of the primary circuit. This property of the coolant, along with a lower pressure in the primary circuit compared to the pressure in the steam-water circuit, eliminates the need for quickly shut down of the reactor unit in the event of an interloop leakiness of the steam generator.

The low volumetric expansion coefficient of the LBC makes it possible to drastically reduce the size of the volume compensator (pressurizer). But, at the same time, it is sufficient for the natural circulation of the LBC in the primary circuit, which ensures reactor emergency cooling down.

The low melting point of the LBC ( $\sim 123.5^\circ\text{C}$ ), close to the melting point of sodium ( $\sim 98^\circ\text{C}$ ), makes it possible to repair the primary circuit equipment and refueling without draining the LBC while maintaining it in a liquid state at a temperature of  $160\text{--}180^\circ\text{C}$  by operation of the heating system or residual heat.

The absence of a change in volume during melting-solidification creates the possibility of multiple freezing and unfreezing of the LBC in the reactor unit, which is safe for the reactor unit equipment. Unfortunately, this property of the LBC became known from the work of foreign researchers much later, and was not taken into account during the operation of the reactor unit, which was en-

visaged only in the liquid aggregate state of the LBC. In practice, this created many unnecessary difficulties and was one of the main reasons for terminating the operation of nuclear-powered submarines with the LBC.

### **Main scientific and technical problems solved during the development of the lead-bismuth-cooled reactors**

The scientific foundations for a new type of reactor with an intermediate neutron spectrum and a lead-bismuth coolant were developed in parallel with the designing of the reactor unit. At this stage of work, the physical theory and methods for numerical calculation of reactors, experimental methods for studying its neutronic characteristics and methods for calculating radiation shielding were elaborated. In addition, the issues of heat transfer in a lead-bismuth coolant were studied, the physicochemical properties of the coolant and the issues of corrosion resistance of steels were investigated, the design and reliability of fuel elements, including those in reactor loops, were substantiated, highly sensitive methods of chemical-spectral analysis of materials were worked out, approaches were developed to designing equipment and ensuring its reliability, constructing circulation circuit diagrams, etc. The NPU operating modes, safety measures, issues of maintenance, repair and fuel refueling were conformed. World-class schools of specialists were formed in the IPPE, OKB Gidropress, OKBM Afrikantov and NITI (Sosnovy Bor, the KM-1 facility) in these areas of work. The most important scientific and technical problems encountered in the course of the practical development of the reactor units are analyzed below.

#### ***Lead-bismuth coolant technology***

Among the main problems that were solved during the development and operation of these reactor units, it is necessary to single out the problem of LBC technology representing a complex of systems and devices that ensure control and maintenance of the required quality of the LBC during long-term operation both under normal conditions of a leaktight circuit and in case of SG leakage, partial depressurization of the circuit during repairs, or refueling. The functioning of this complex is necessary to exclude corrosion of structural materials and slagging of the circuit with lead oxides.

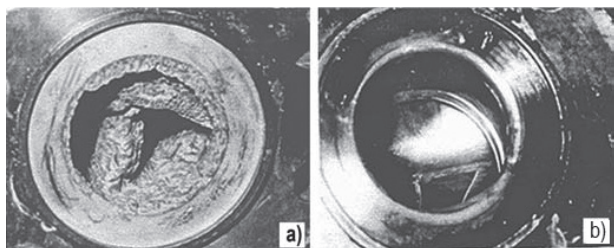
The importance of this problem was understood after the reactor accident at the first pilot NPS of Project 645 in 1968. Appropriate methods and devices were developed even later, when the construction of the planned series of NPSs of Projects 705 and 705K was completed. Therefore, it was not possible to place the necessary devices as standard ones in the NPU. Some of the devices were assembled in the basic facility, which required once a year to be connected to the NPU. It should be noted that this experience was fully taken into account in the development of next-generation reactor projects for civil nuclear power. All the devices for monitoring and maintaining the quality of the coolant (it is necessary to control only



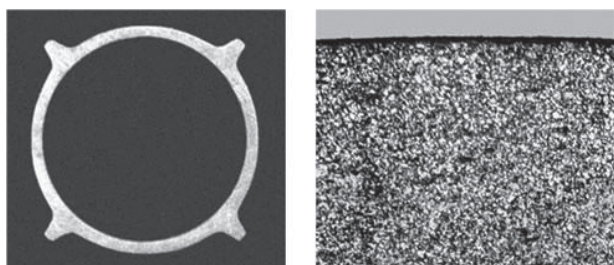
one parameter, i.e., the content of oxygen dissolved in the LBC) are located in the NPU as standard ones: they operate automatically.

To solve these problems, under the general guidance of V.I. Subbotin and B.F. Gromov, devices were developed that ensure the chemical reduction of lead oxide (Yu.I. Orlov), dosing devices for maintaining the required concentration of a corrosion inhibitor in the LBC, i.e., dissolved oxygen, (P.N. Martynov), appropriate sensors that allow monitoring the quality of the LBC and protective inert gas (B.A. Shmatko), special filters for cleaning the LBC from insoluble impurities (A.K. Papovyants). Corrosion resistance of materials is ensured by appropriate alloying of steels (A.Ye. Rusanov), preliminary application of protective oxide coatings (A.P. Trifonov and G.S. Yachmenev) and maintenance of the required dissolved oxygen concentration in the LBC.

Figs 2, 3 show the results of work on the LBC technology (Zrodnikov et al. 2003) and ensuring the corrosion resistance of steels (Rusanov et al. 1999).



**Figure 2.** Hydrogen cleaning of the pump facility pipeline in 1980: **a.** Before cleaning; **b.** After cleaning.



**Figure 3.** Corrosion-free fuel rod cladding (EP-823SH steel) after testing in the LBC at a temperature of 600 °C for 50,000 hours.

### *The dual role of oxygen*

The development of high-temperature hydrogen regeneration of the LBC and the primary circuit using an ejection device (Yu.I. Orlov) ensured the delivery of small bubbles of a hydrogen-containing gas mixture for cleaning from oxide deposits (slags), which were the main cause of the accident on the NPS K-27 and the poor operation of the 27/VT facility in the second campaign after lengthy work on the modernization of the reactor unit with a depressurized primary circuit. At the same time, it turned out that when corrosion tests were conducted at temperatures of fuel claddings of about 600 °C, incomprehensible results appeared. In one case, samples of tubes with a diameter of 12 × 0.4 mm simply dissolved – they were not found in

the coolant. In other experiments, they withstood 1000 or even 2000 hours without any signs of corrosion.

The main corrosion protection of steel in lead-bismuth is an oxide coating on the surface of the steel, i.e., thin layers of iron and chromium oxides  $\text{Fe}_3\text{O}_4$ ,  $\text{Cr}_2\text{O}_3$ . But it turned out that if the steel was oxidized in air at 600 °C, then the film was loose, providing no protection at all. Oxidation must be carried out at a low partial pressure of oxygen: in an atmosphere of carbon dioxide, water vapor or in lead (lead-bismuth) with oxygen dissolved in it. It was found that the oxide coating formed in this way had a quality that was very important for practice, i.e., “self-healing” after mechanical damage, if the required concentration of oxygen dissolved in lead-bismuth was maintained.

M.N. Ivanovsky and B.A. Shmatko proposed a device for measuring the concentration of dissolved oxygen in the coolant. As it turned out, oxygen is present in the coolant in two forms: active and passive. In the chemical reaction of the formation of an oxide film on the steel surface, only dissolved active oxygen is involved. But the oxygen that is already bound in the form of iron oxides cannot take part in the oxidation of iron in the same steel as it has already lost its thermodynamic potential. Since then, the coolant technology has received scientific justification. Today, all the above is very well studied and described in (Handbook 2015).

It is required to maintain the concentration of dissolved oxygen in the desired range and, if the concentration is very low, oxygen should be added in order to maintain a stable state of the protective oxide films. Therefore, on the NPSs, 100 g of air or the corresponding amount of oxygen was supplied once a year to the gas system per circuit, in which there were about 50 tons of coolant. Thermodynamic activity was measured, then excess oxygen was removed using hydrogen regeneration.

### *Ensuring radiation safety during works related to contamination of air and equipment surfaces with polonium-210*

The specificity of the LBC is the formation in it of the alpha-active radionuclide polonium-210 with a half-life of ~138 days when irradiated with bismuth neutrons. The radiological hazard of the coolant manifests itself when the LBC or the gas in contact with it enters the serviced premises, which took place during accidents and repairs of NPS NPUs and ground prototype facilities during their development.

As the experience of operating the NPS NPUs has shown, the yield of polonium aerosols and the radioactivity of air, in accordance with the laws of thermodynamics, sharply decrease after the temperature drops and the spilled LBC solidifies. The rapid solidification of the spilled LBC limits the area of radioactive contamination and allows the spilled LBC to be disposed of as solid radioactive waste. The low concentration of polonium in the LBC (at the level of  $10^{-6}$  at.) and the formation of a thermodynamically stable chemical compound of polonium with lead determine the low concentration of polonium-210 in the air during emergency depressurization of the primary circuit.

To carry out maintenance and repair work on “dirty” equipment or to remove leaked coolant (up to 20 tons at the 27/VT facility), measures for individual and collective protection of personnel (respirators, protective clothing, ventilation) were developed. In addition, methods were developed for decontaminating equipment and fixing activity on surfaces, including techniques for carrying out maintenance and repair work that reduce the risk of dangerous amounts of polonium-210 entering into the body or on the skin (Pankratov et al. 2005).

All the personnel involved in the work were subjected to periodic medical examinations, and based on numerous radiometric analyzes of bioassays of the personnel (both military and civilian), and it was objectively established that there were no cases of the presence of incorporated polonium in the human body above the permissible limits. This confirms the high efficiency of the applied means of individual and collective protection, the correct choice of technology and the organization of maintenance and repair work. This was also facilitated by the relatively fast excretion of polonium from the body as a result of metabolic processes (the effective half-life is about 30 days) and the very low molar concentration of polonium in the liquid metal coolant (LMC), which accordingly reduces its volatility in comparison with pure polonium.

One of the papers published in the USA (Wiggs et al. 1991) presented data from a retrospective analysis of mortality among a large group of workers employed in work with allocated Po-210 in 1944–1972 at the Mound Facility and controlled by internal exposure to Po-210. The authors analyzed the medical reports of radiometric analyzes (over 160 thousand bioassays) of a group of white men in the amount of 4402 (104,326 man-years) who worked with Po-210 during this period, and compared the results of observations with official data on the causes of death of 987 people from this group for the period from the start of work to January 1984. They also compared the mortality statistics of this group with similar data from two control groups of people (average for the United States and for the state of Ohio) and concluded that there was no relationship between the received doses of internal radiation for account of incorporated polonium up to 1 Sv (100 rem) and the level of mortality due to malignant tumors. Almost all trends characterizing mortality from various cancers in the studied group of workers were negative, i.e., mortality was even somewhat lower than in the two control groups.

Therefore, the generation of polonium-210 in the LBC is not an obstacle to its use as a coolant for nuclear reactors; although, of course, all measures to ensure radiation safety must be provided for.

#### ***“Freezing-unfreezing” the LBC in the reactor units***

It was an important practical problem to substantiate the possibility of repeated “freezing-unfreezing” of the reactor unit with the LBC, which could be required during long-term stays of nuclear-powered submarines. The fact that the LBC did not change its volume during melting

(solidification) (Handbook 2015) and had a sufficiently high ductility with low strength in the solid state made it possible to exclude damage to the reactor units during the transition of the LBC from the liquid to the solid state and its further cooling to ambient temperature. In order to safely “unfreeze” the LBC, OKB Gidropress worked out a special regulation for the temperature-time mode of heating tested on large-scale models and on the starboard reactor of the Project 645 NPS after its long stay in the “frozen” state. However, this regime was not put into practice in association with the decision to terminate the further operation of nuclear submarines of this type adopted in the mid-1990s.

One more property of the LBC should be noted, i.e., a slow spontaneous increase in its volume in the solid state, reaching about 0.5% in two months, due to changes in the crystal structure (Pylchenkov 1999). In specially designed experiments, a slow “self-extrusion” of the LBC through a small hole was observed. However, the low hardness and high ductility of the LBC in the solid state excluded the occurrence of damage to the equipment.

It should be said that the property of the LBC to solidify at 123.5 °C in some cases also played a positive role. For example, when the unloaded core is stored in a tank with the “frozen” LBC, an additional protective barrier is formed in the way of radioactivity release into the environment.

#### ***Ensuring high reliability of the steam generators***

The first modifications of NPU SGs with the LBC, as well as NPUs with water-cooled reactors (WWR) for NPSs, were not very reliable. However, lead-bismuth submarines with leaking steam generators went out to sea and returned normally. Steam entering the primary circuit, the pressure in which is lower, bubbled through the coolant and condensed in the emergency condenser of the gas system.

The low reliability of the first generation SGs was associated with the choice of the material of the pipe system which changed as experience gained. The technology of reliable embedding of tubes into tube sheets and the design of the tube spacing unit in a bundle were also worked out.

The problem of tube spacing was revealed during testing the MP-7 SG as part of the 27/VT-5 facility (the second campaign). Shortly after the commissioning, regular leaks began in SG tubes made of pearlitic steel, corrosion-resistant both in the LBC and in the aqueous medium, subject to the water chemistry requirements. Cutting out the damaged tubes showed that, at the points of contact with the spacer plates, the outer surface of the tubes acquired a hexagonal shape as a result of vibration wear, with a corresponding local decrease in wall thickness. This led to the rupture of the tubes by steam pressure due to loss of strength.

It became clear that it was necessary to develop a modernized SG design with a rigid spacing of the tube bundle. This design (MP-7M and MP-8M for the OK-550 and BM-40/A reactors, respectively) was developed by OKB Gidropress. Tests at the OKBM full-scale facility confirmed the exceptionally high reliability of the new spacing

unit. The manufacture and installation of modernized SGs required a halt in the construction of six NPSs, standing on the stocks of factories in Leningrad and Severodvinsk.

All these measures led to the fact that, if at the 27/VT facility and the reactor unit of the Project 645 NPS, SG leaks were the rule, then at the serial OK-550 and BM-40/A reactor units they became an extremely rare exception (apart from massive corrosion damage to the SG tubes at the BM-40/A reactor unit on the lead NPS K-123 (Project 705K, Order 105) as a result of a long secondary circuit water chemistry upset).

## Brief analysis of accidents (Gromov et al. 1999)

The entire period of developing the lead-bismuth-cooled reactor units is clearly divided into two large stages. The first stage of developing this new reactor technology, which took place in the absence of any domestic and foreign experience and very short deadlines for constructing RUs for NPSs dictated by the political situation (the armaments race was in full swing), was accompanied by a number of difficulties and failures.

It was at this stage that accidents occurred on pilot NPSs that required the early termination of the operation of these submarines. Moreover, only on the very first pilot NPS of Project 645 the cause of the accident was associated with the use of the LBC. On the pilot NPS of Project 705 (Order 900), the cause of the accident was associated with the poor quality of equipment installation at the shipyard and violations of the operating regulations. (The history of the construction and experience of operating the NPSs of Projects 705 and 705K with the memoirs of the participants are described in detail in B.V. Grigoriev's book *A Ship Ahead of Its Time*. St. Petersburg: Typhoon Publ., 2003, available on the Internet).

The reason for the first accident, as a result of which part of the core melted due to slagging, was due to the lack of knowledge of the coolant technology at that time.

The second accident on the pilot NPS (Project 705, Order 900) was associated with massive corrosion damage to the auxiliary pipelines of the primary circuit due to prolonged ingress of moisture saturated with chlorides contained in the thermal insulation material onto the outer surface of the pipes. Moisture ingress was associated with steam leakage through the steam generator cover sealing gasket.

In addition, on the lead NPS K-123 (Project 705K, Order 105), during the factory repair, the reactor unit was replaced with a new, pre-fabricated one, due to the end of life of the steam heating system pipes, in which steel pipes were erroneously used at the plant, lacking the required corrosion resistance. Prior to this, as a result of a secondary circuit water chemistry upset, a massive corrosion damage occurred to the SG pipe system, which caused steam to leak into the primary circuit, which, as a result of incorrect actions of the personnel, led to the leak-

age of 250 liters of the LBC into the reactor compartment. However, none of the crew members was injured.

On the NPS K-373 (Project 705, Order 910), for unknown reasons, europium compound grains from the absorbing rod material were released into the control and protective system (CPS) servo drive mechanism, which drastically worsened the radiation situation in the reactor compartment and required the reactor unit to be shut down when about 70% of the campaign was depleted. The accident caused no injuries.

## Difficulties related to basic maintenance of NPS reactor units

First of all, it was the unpreparedness of the coastal base infrastructure to ensure uninterrupted supply of steam to the primary steam heating system to maintain the liquid aggregate state of the LBC. As a result, these submarines were in the base with NPUs operating at low power (0.5% of the rated value), which led to increased resource depletion and additional crew loading.

Difficulties in maintaining the NPUs at the NPS bases and refueling should include the need for periodic (once a year) connection of the NPUs through flexible pipelines to the base unit for routine maintenance related to the coolant technology. This was due to the impossibility of introducing a number of coolant technology devices as regular ones into the NPUs, which were absent at first in the project, due to the completion of the installation of the NPUs of NPSs under construction.

When a NPS was parked in the base, it required the supply of electricity of non-standard parameters (current frequency = 400 Hz), which was determined by the specifics of its electrical power system, which made it possible to significantly improve the weight and size characteristics of electrical equipment. Through the hatch it was possible to extract the generator and electric motors for repair or replacement. For the NPU itself, this current frequency was not required.

The noted difficulties, typical for specific designs of NPS NPUs, were among the objective reasons (along with the fact that the NPSs of these projects no longer met the requirements for acoustic stealth that had greatly increased over 20 years) for making the decision to terminate the operation of NPSs of this type. There were also subjective reasons for this decision.

The technology for carrying out repair work and refueling is described in the report (Sazonov et al. 1999).

## Main results of operating the lead-bismuth-cooled reactor units

The characteristics obtained in the course of tests and operation of the nuclear power unit, such as capacity, mode parameters, campaign duration, reactivity margin, reactivity



vity coefficients, effects of poisoning, temperature distributions, dynamic parameters, radioactivity of the coolant, and dose rates of neutron and gamma radiation behind the shield coincided quite well with the calculation results. The cores and control rods system, which ensured the development of the design energy resource, showed high efficiency. The automated control system ensured the input of the reactor unit from the subcritical state of the reactor in about 30 minutes from pressing the “START” button to accepting the load on the turbogenerator. The time to reach full power from the turbogenerator mode was 90 seconds.

Due to the fact that the core is part of the non-separable removable part of the reactor, technical means of refueling were developed, which differed from similar means used for channel-by-channel fuel change in WWR reactors. In addition to the refueling equipment itself, the complex of fuel reloading equipment should also include lifting equipment and a dock for installing the NPS on a rigid base (the reactor cores of the Project 645 NPSs were refueled afloat). For this purpose, a complex of equipment and facilities was provided on a specialized base that ensured the process of fuel reloading, including long-term storage of unloaded fuel until it was sent for processing.

Experience in developing and operating the lead-bismuth-cooled NPU as part of NPSs and ground-based prototype facilities allows us to draw a number of important conclusions on the layout and equipment of the primary circuit.

The best performance should be expected with an integral (monoblock) layout of the primary circuit equipment, which makes it possible to completely eliminate the pipelines and fittings of the LBC.

The most convenient design scheme of a steam generator is the one where liquid metal circulates in the intertube space, and water or steam circulates in tubes. With this design, it is possible to repair the steam generator by plugging individual tubes that have lost their tightness, without dismantling the SG or opening the primary circuit.

Standby, start-up and cool-down modes are performed most simply when the steam generator is structurally divided into evaporator and superheater sections, and the evaporator section operates in the mode of multiple circulation of the steam-water mixture through the separator. At the same time, water with a temperature higher than the melting point of the LBC is supplied to the steam generator.

It is advisable to use instead of turbo-driven pumps, mechanical pumps with gas-tight electric motors or magnetohydrodynamic pumps, when taking measures to reduce the hydraulic resistance of the primary circuit for the LBC circulation.

Among the positive qualities of the lead-bismuth-cooled NPU identified during operation, we should note ease of operation, high maneuverability and short time to enter the power mode from the reactor subcritical state, and ability to quickly change the coolant circulation mode with a significant change in its flow rate. The possibility of operating the reactor unit with a small leak in the SG pipe system, the high maintainability of the SG, and stable operation of the reactor unit at any low power le-

vels were confirmed. Practically complete generation of the design energy reserve by the cores was ensured under normal and permissible states of fuel cladding integrity. During homeporting, repairs and fuel reloading, liquid radioactive wastes (LRW) were practically not generated.

The second stage of developing the lead-bismuth-cooled NPUs on NPSs was characterized by their reliable long-term operation on six serial submarines: their design underwent the necessary changes arising from operating experience and analysis of the causes of the accidents that occurred. Over the last 10 years of operating the reactor units, after the introduction of means and methods for maintaining the required quality of the coolant, there were no problems either with corrosion of structural materials in the primary circuit or with deviations from the norms regarding the cleanliness of the primary circuit.

Since the experience of using the LBC on the Project 705 NPSs was interpreted ambiguously, at the suggestion of the Commander-in-Chief of the Navy in 2008, Rosatom created an interdepartmental working group, led by Vice-Admiral, Academician A.A. Sarkisov, from representatives of all interested organizations, which reviewed the operating experience. The Conclusion of the working group states that “the results of the operation of reactor units on nuclear-powered submarines of Projects 705 and 705K were recognized as positive:

- the total operating time in all modes was about 80 reactor-years, it confirmed the advantages and main characteristics laid down in the project and was sufficient to identify design and technological shortcomings in order to determine the main directions for improving the reactor units;
- accidents and incidents took place in the initial period of their operation, which was typical for other types of units, including those with pressurized water reactors.”

All the accidents that required the early termination of operation of two lead-bismuth-cooled NPSs occurred on the first pilot NPSs K-27 and K-64. On the lead NPS K-123 of Project 705K, after six years of operation, it was necessary to replace the BM-40/A NPU with a new one, which was prefabricated due to the end of life of the steam heating system pipes made of ordinary stainless steel, which were erroneously mounted in the reactor unit, instead of the pipes made of special corrosion-resistant steel of the same diameter. The serial NPSs were reliably operated for their intended purpose.

Works on the development of this direction were highly appreciated by the state: two Lenin and one State Prizes were awarded, A.I. Leipunsky and V.V. Stekolnikov (chief designer of OKB Hidropress) were awarded the Title of Hero of Socialist Labor.

It is impossible to list all the participants in this work, who also laid the foundations for future development, but the main actors who received high awards (A.I. Leipunsky and V.V. Stekolnikov and some others have already been mentioned) should be named: in IPPE: B.F.

Gromov, K.I. Karikh, O.G. Komlev, V.A. Kuznetsov, V.A. Malykh, I.P. Zasorin, G.I. Marchuk, D.M. Ovechkin, D.V. Pankratov, Yu.G. Pashkin, V.N. Stepanov, V.I. Subbotin, G.I. Toshinsky, V.M. Troyanov, V.V. Chekunov; in OKB "Gidropress": V.I. Akimov, M.P. Vakhrushin, A.V. Dedul, Yu.G. Dragunov, Ye.V. Kulikov, G.D. Lunev, V.S. Stepanov, G.A. Tachkov, V.A. Chistyakov, B.M. Sholkovich; in OKBM: I.I. Afrikantov, F.M. Mitenkov, N.M. Tsarev, M.V. Smirnov; in Minatom: V.P. Pigalev.

Figs 4, 5 show the NPSs of Projects 645, 705 and 705K, their main creators and commanders.

In conclusion, we present the opinions of three experts on NPSs of Projects 705 (705K).

- *Fedor Mitenkov, academician, winner of the Global Energy Prize, former director of OKBM Afrikantov*: "Operation of serial objects with nuclear power units using the liquid-metal Pb-Bi coolant confirmed the design efficiency of circuit and design solutions for equipment and nuclear power units in general ... However, the successful operation of the serial submarines in general revealed such significant



Figure 4. NPS K-27 of Project 645 with the first-generation LMC.

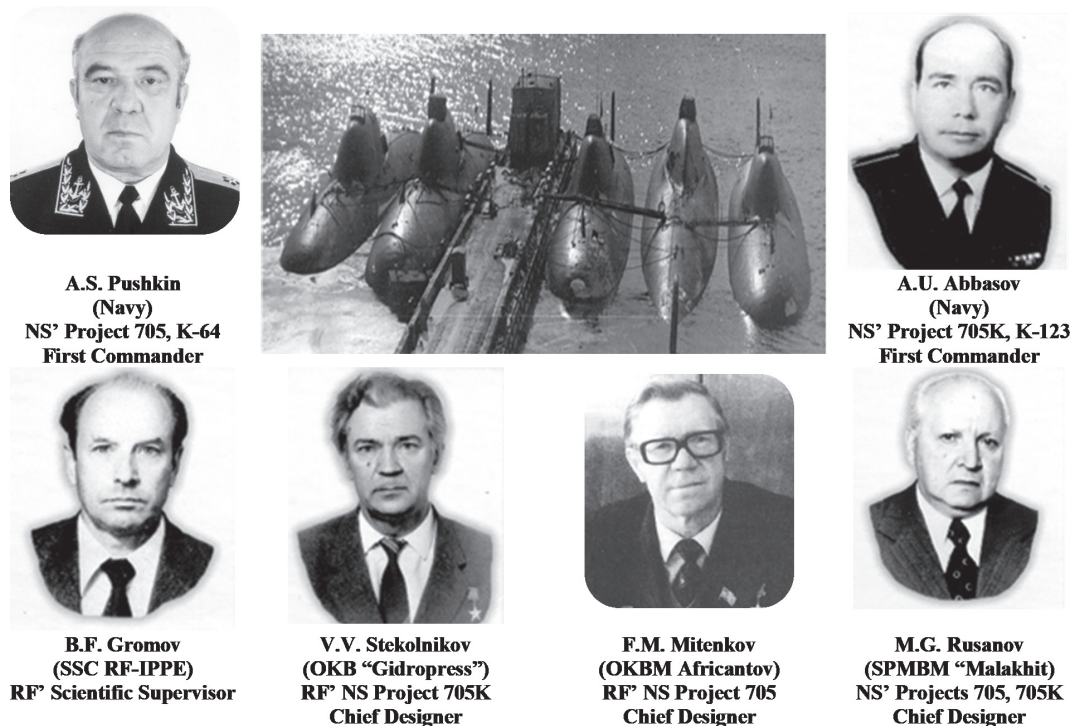


Figure 5. NPS with the LMC of Projects 705 и 705K.



shortcomings as much more difficult conditions for maintaining the submarines in the inter-cruise period at the base compared to nuclear power units on the water, as well as increased noise. But it should be borne in mind that the ways to overcome the noted shortcomings are quite understandable” (*Creators of the Nuclear Age. Reflections on the Past*. Moscow: IzdAT, 2004, pp. 55–57).

- Norman Polmar, *US government adviser*: “I can congratulate those who designed and built “Alpha”. They were ahead of everyone in the West by 20–25 years. I regret that there are no more submarines of this project, but as a US citizen and naval specialist, I am glad that they are gone, since these submarines posed a serious threat to the US Navy” (Author’s blog Gennady Drozhzhin, 00:00, March 28, 2012).
- Gennady Drozhzhin, *captain of the first rank, member of the Presidium of the United Council of Submarine Veterans*: “Every single one of these wonderful submarines was destroyed without having served even half of

their life, and if they were modernized to reduce noise and equipped with a new hydroacoustic complex, today they would become unconditional “killers” of US SSBNs and their aircraft carriers” (Author’s blog Gennady Drozhzhin, 00:00, March 28, 2012).

## Conclusion

In the process of developing and operating the lead-bismuth-cooled reactors for NPPs, a unique nuclear technology was mastered on an industrial scale. The initial period of developing this technology, which took place in the absence of the necessary knowledge and experience, was accompanied by a number of difficulties and accidents, the causes of which were definitely clarified and eliminated, which is confirmed by the reliable operation of these NPUs on serial NPPs. On the basis of the critically analyzed operating experience, the design of a civil-purpose reactor unit (SVBR-100), a modular type, that meets the requirements of Generation IV, is currently being developed.

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