# The First in the World Reactor with Lead-Bismuth Coolant (Facility 27/VT). How that Started

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# Introduction (1)

- Sixty years ago on December 25, 1958, the first criticality of the first in the world reactor with lead-bismuth coolant (LBC) was realized at Facility 27/VT in the State Scientific Center of the Russian Federation – Institute for Physics and Power Engineering (SSC RF-IPPE). It was a ground facility-prototype of nuclear power facility (NPF) at the first nuclear experimental submarine of Project 645 (K-27) with two lead-bismuth cooled reactors. The developers of reactor facility (RF) were Institute for Physics and Power Engineering (Research Manager) and Experimental Design Bureau “Gidropress” (Principal Designer).

# Introduction (2)

- In the USSR just as in the USA, works on construction of nuclear power facilities (NPF) for NSs were launched in two directions, namely: pressurized water reactors (PWR) and reactors with liquid-metal coolant (LMC). However, in contrast to works carried out in the USA, where sodium was selected as LMC and did not justify itself in the process of operating NPFs at NSs, after certain difficulties and failures, the LBC cooled reactors were mastered and successfully operated at serial NSs of Project 705 (705K).
- Development of RFs with LBC was realized in conditions of absence of necessary knowledge and experience. Moreover, the fixed directive terms of work completion practically eliminated the opportunity for performance of related scientific and research works that caused a number of failures at the stage of mastering of that technology.

# 1 Key Scientific and Technical Problems Solved in the Process of Mastering of RFs with LBC

## *1.1 LBC Technology (1)*

- The seriousness of that problem was sized up after the reactor accident occurred at the first experimental NS of Project 645 in 1968.
- The relevant measures and equipment were developed later, when construction of the planned series of NSs of Projects 705, 705K was almost completed.
- For that reason, there was no opportunity to install the necessary equipment within the RF structure as standard ones. The certain devices were arranged in the base facility that required their connection to the RF once a year.

## *1.1 LBC Technology (2)*

- **During the period of development of the measures on coolant purifying, it was an intention to become extremely skilled in purification. And so, that goal was achieved. However, when corrosion tests were performed under temperatures of fuel elements claddings being about 600 °C, some strange results were obtained. There was an incident when the tubes of 12×0.4 mm in diameter were fully dissolved (they were not find in the coolant). In other experiments, in which they were tested during 1000 or 2000 hours, no signs of corrosion were detected. That was difficult to understand.**
- **Development of high-temperature hydrogen regenerating of LBC and primary circuit for purification from oxide deposits (slags) that was worked out by Yu.I. Orlov was a great advance because plugging by oxides in the core was a major cause of the accident at the NS K-27. Moreover, that was also a cause of insufficient operation of Facility 27/VT in the second lifetime after realization of extended works on upgrading of the RF with untightness in the primary circuit.**

## *1.1 LBC Technology (3)*

- **Everybody was at a loss. To clear up the reason of those phenomena, during approximately two or three years the continued meetings were held by A.I. Leypunsky unless two IPPE scientists, namely M.N. Ivanovsky and B.A. Shmatko, designed a device for measuring of concentration of dissolved oxygen in coolant.**
- **As it was cleared later, the oxygen was existing in coolant in two forms: in an active form and in passive one. The passive oxygen is existing in coolant in a form of iron oxides $Fe_3O_4$ that is a thermodynamically resistant chemical compound.**
- **Actually, the iron impurities are always existing in coolant, the oxygen is taken by iron from lead-bismuth alloy very actively and the suspended particles of bound oxygen are formed.**

## *1.1 LBC Technology (4)*

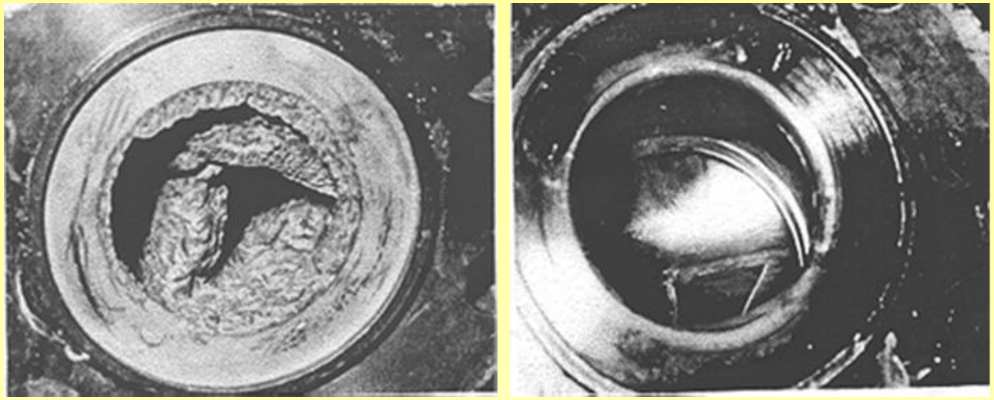
- **The invented device was named “activometer” or a sensor of thermodynamic activity of oxygen. At the output it indicated the potential difference depending on concentration of dissolved active oxygen. When those devices were installed at the facilities, everything became clear. The active oxygen was separated from passive one and the purpose was to maintain the concentration of thermodynamic active oxygen within a specified range. From that time the application of LBC technology has been scientifically justified.**
- **After that it was necessary to master to maintain the concentration of dissolved oxygen within the required limits in the process of operating. It was clear that there must not be oxidation, the circuit must be tight, the gas must be purified. The oxidation was not allowed, the circuit must be tight. Thus, it was not required to perform realization of high-temperature hydrogen regeneration for removal of excess oxygen that would form lead oxides, i.e. slags, which would deposit as a solid phase in the cold parts of the circuit and plug the tubes.**

## *1.1 LBC Technology (5)*

- **From the other side, the oxygen must be maintained within the necessary range and in case of very low concentration it should be added for the purpose to maintain a stable state of protective oxide layers. For that reason, once a year at the submarines, 100 g of air or oxygen (it is of no importance) was inserted into the gas system in the circuit, in which there were 50 tons of coolant. Thermodynamic activity was measured, then the excess oxygen was removed by hydrogen regeneration.**
- **Later P.N. Martynov developed the mass-exchange devices, which made possible realization in an automated mode the maintenance of concentration of dissolved oxygen at the required level by a signal received from the activometer, and filters purposed to remove undissolved impurities, which could not be regenerated by hydrogen.**

# 1.1 LBC Technology (6)

## *The Results of Works on LBC Technology Mastering*



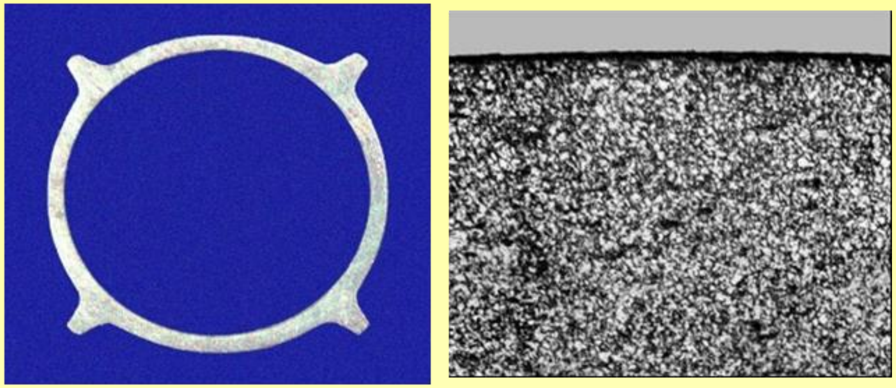


**Fig. 1. Hydrofining in the pump facility pipeline in 1980**
**Left: prior to hydrofining,**
**Right: after hydrofining**

**Fig. 2. No signs of corrosion in the fuel element cladding made of steel EP-823SH after 50000 hours of testing in LBC under 600 °C**

# *1.2 Providing of Radiation Safety for Works Associated with Polonium-210 Contamination of Air and Equipment Surfaces (1)*

- **The specific feature of LBC is that when it is irradiated by bismuth neutrons, the alpha-active radionuclide of polonium-210 with half-life of approximately 138 days is formed. Radiologic hazard of coolant can be revealed when LBC or contacting with LBC gas is penetrated in the serviced rooms that happened in events of accidents and repair woks performed at RFs of nuclear submarines and ground facility-prototypes during the period of their mastering.**
- **As experience of RF operating at NSs has revealed, in correspondence with thermodynamics laws, the release of polonium aerosols and air radioactivity are reducing sharply after lowering of temperature and solidifying of spilled alloy. Quick solidifying of spilled LBC is restricting the area of radioactive contamination and makes possible removal of spilled LBC as solid radioactive waste.**

## *1.2 Providing of Radiation Safety for Works Associated with Polonium-210 Contamination of Air and Equipment Surfaces (2)*

- **The personnel, who took part in those works, was subjected to periodic examinations, and based on multiple radiometric analysis of biological tests of the personnel (both military and civilians), the absence of accidents with existence of incorporated polonium in human organisms over the permissible levels was specified.**
- **That fact validated a high efficiency of used individual and collective protection measures, the right option for the technology and correct organization of repair and maintenance works. It was also promoted by comparatively quick polonium washout from the human organism resulted from metabolic processes (effective period of semiejection was approximately 30 days) and very low molar concentration of polonium in LBC that lessened its volatility as compared with pure polonium.**

## *1.3 “Freezing-Unfreezing” of LBC in the RF (1)*

- **The vital issue was justification of the opportunity of multiple “freezing-unfreezing” of LBC cooled RFs that could be required for long standings of NSs. Lack of change in LBC volume upon melting/solidifying and sufficiently high plasticity under low strength at a solid state made possible elimination of RF damage while LBC was converted from a liquid state into solid one and upon its further cooling to the environmental temperature.**
- **For the purpose of safe “unfreezing” of LBC, the specialists of EDO “Gidropress” developed the special regulations on a temperature-time heating regime tested at large-scaled mock-ups and RF of the NS right side of Project 645 after it had been stood in “frozen” state for a long time. However, that regime was not implemented in practice due to the decision taken in the middle 90th, which ordered to shut down further operation of that type NSs.**

## *1.3 “Freezing-Unfreezing” of LBC in the RF (2)*

- **It should be pointed out that sometimes a LBC property to solidify under 123.5 °C was positive. For example, when the unloaded core is stored in the tank with “frozen” LBC, the auxiliary protective barrier is formed on the way of radioactivity release into the environment.**

## *1.4 Providing of High Reliability of Steam Generators*

- **The reliability of first variants of steam generators (SG) of LBC cooled RFs as well as those of RFs with pressurized water reactors (PWR) for NSs was not high. However, with leaked SGs the NSs with LBC cooled RFs went to sea and came back without incidents. The steam that penetrated into the primary circuit bubbled via the coolant and was condensed in the emergency condenser of the gas system. Then that radioactive condensate was discharged in sea.**
- **Low reliability of the first generation SGs was caused by selection of the material for the SG tube system, which were changed as experience had been gained.**
- **Moreover, the technology of reliable embedding of tubes in the tube plates (the way from mechanical beading with welding sealing to explosion expander and then to hydraulic expander with electron-beam welding was passed) and design of the unit of tube spacer in the cluster, which required serious upgrading, were developed.**

# 2 Incidents and Accidents at Facility 27/VT. Experience as "a Son of Agonizing Errors"

## *2.1 Core Assemblage and Hammer (1)*

- **The core design of that reactor was loose. I.e. the core was without cassettes. That was a set of rod fuel elements of 12 mm in diameter. For the next cores the fuel elements were integrated in clusters, namely hexahedral heat-releasing subassemblies that was much more convenient for assembling of the core.**
- **The technologists tried hard to make the straight-line fuel elements, nevertheless, there was a little bending, bending deflection was 1 – 1.5 mm. Core assembling was performed in a horizontal position from a bottom of the reactor removable unit, the lid of the basket was removed. For that purpose, the reactor removable unit was inserted in a special turnover, i.e. a mechanism that made possible its swinging in a horizontal position.**

## *2.1 Core Assemblage and Hammer (2)*

- **Performance of horizontal laying of fuel elements was started. The bottom row of fuel elements was laid, plugs were put tightly touching each other. The second and third rows of fuel elements were laid without problems. However, the difficulties arose when it was necessary to lay the last upper row (or two rows). Due to the fact of gathered deflections, it turned out that there was very little free space for installation of fuel elements, and it was not possible to insert the last fuel elements.**
- **The responsibility for next developments was taken by D.M. Ovechkin, who was Chief Engineer of IPPE, an Interior Ministry Lieutenant Colonel with determinate character. We were horrified (especially V.A. Malyh, who was a designer-technologist of the fuel element) when D.M. Ovechkin inserted the fuel elements by hands to their places (to the most possible positions) and then hammered them by a mallet (wooden hammer). The physicists could not predict the further events: either the welds would crack or not. In brief, he hammered all fuel elements. Further operation revealed that the tightness of fuel elements was not lost.**

## *2.2 First “Freezing” (1)*

- **Assembly works were ended, the heating system was switched on and we started to make preparations for intake of lead-bismuth. At the very beginning of the process of reactor filling, the coolant stopped to flow from the monjuce. So, that meant the alloy “froze” somewhere and “bear” was formed. The indications of all thermocouples showed heating everywhere. And K.I. Karih understood what happened.**
- **At Facility 27/VT the heating system of the reactor vessel was in a form of steam-jacket. The steam was supplied into it and then was blown out over the second tube (an upwardly mounted tube was designed for steam supplying and below mounted tube was designed for condensate blowing out). Further at all other reactors the steam was not supplied into the jacket, but it was supplied into the heating coiler, and the jacket only protected the reactor against mechanical damages. The valve designed for steam supplying into the jacket was not fully tight. However, the pressure existed forward of the valve.**

## 2.2 First "Freezing" (2)

- During the time when the reactor was cold, the steam slowly flowed through that untightness. Flow rate of steam was very small, the vessel was cold, the steam was condensing in the jacket and it turned out that the whole jacket was filled with cold condensate. For that reason, when the first portion of alloy flowed and came to a cold place, the alloy solidified. K.I. Karih ordered to open in full all discharge valves from the steam-jacket. In a certain time, the steam pressure pressed out the condensate, and heating started right after that.
- Everybody was scared that solidified alloy could cause such stresses in structures, which could damage them. (For example: in an event of terminating of heating supply in winter, the radiators should be drained, otherwise they could be broken by formed ice.) From that the unjustified requirement originated (today it is clear), namely: to maintain the liquid state in the primary circuit. However, finally everything was OK.

## 2.3 Coolant Leaks (1)

- **Coolant leaks in the primary circuit were one of the serious problems arisen right after the beginning of operation. The leak can be identified very easily as while the circulation pumps are operating, the circuit is filled with coolant, and lowering of the LBC level in a buffer chamber under the constant temperature is a sign of coolant leak.**
- **In the buffer chamber the leak reversion pumps (LRP) are installed, which provide anti-cavitation static suction head at the suction of the main and auxiliary circulation pumps. LBC flow rate produced by the LRP is supplied to the groove seals of the shafts of the main and auxiliary circulation pumps (these are vertical pumps with oil seals of the shafts regarding helium, which eliminate air ingress into the primary circuit gas system and release of radioactive gas into the compartment air). From the groove seals the coolant is discharged naturally (self-flowing) through the leak draining pipelines into the buffer chamber, where the coolant is also transferred over the pipelines of SG air vents.**

# 2.3 Coolant Leaks (2)

- Thus, in addition to the main circulation circuit of LBC in the RF there is an auxiliary circuit of draining and leak reversion. A leak reversion pump is providing flow rate of about 15 $m^3$ per hour under pressure of 15 atmospheres. If the circuit is tight and there is no leak, the LBC level in the buffer chamber is unchangeable as it is only reacting on temperature changes. Thus, while operating at a stable power, the level began to decrease slowly. At first, the worst thing was not expected, it was assumed that a level-meter had failed and the second level-meter was used. The second level-meter also indicated level decreasing. So, shutdown had to be realized for the purpose to detect leak. Otherwise, the facility could not operate.
- And that was performed: power was reduced, the reactor was shutdown. Works on dismantling of protection, tight barrier were launched as weak rarefication was maintained in the tight compartment for the purpose not to release the radioactivity into the living part of the compartment.

## *2.3 Coolant Leaks (3)*

- **In the bilge part (it was a ship compartment) there was a big puddle of solidified lead-bismuth on the bottom of the compartment. The point of leak and leak cause had to be detected. The necessary measures had to be developed for the purpose to assure no occurrence of such events at the NSs in future, as it was the first facility and the next NSs had been already standing in building berths.**
- **With due account of radiation, the access to the specified compartment could be carried out in two or three days without extra-irradiating as induced gamma-activity of lead-bismuth was very low and only caused by impurities, mainly by manganese. Therefore, long-term works could be performed. Of course, there was polonium contamination in the air, so the personnel worked in protective clothing and respirators. There were many auxiliary pipelines and all of them had to be examined. The pipelines, via which the coolant was supplied to the primary circuit from a leak reversion pump, coolant was reversely drained, drain pipelines, air vents – all those were tubes with a small diameter.**

## *2.3 Coolant Leaks (4)*

- **They were tied around by companion-tubes of steam heater. That decision was made as the coolant had to be maintained in a liquid state, i.e. on each pipeline two tubes of small diameter were mounted, everything was heat-insulated on the outside.**
- **When heat-insulation was dismantled, the companion-tubes were cut and put off, the coolant tubes appeared. Everybody saw that on some pipelines there was a net of corrosion cracks with angularly of 45 degrees. All tubes in the primary circuit were made of austenitic stainless steel that was considered to be the most corrosion-resistant one.**
- **All those auxiliary tubes could not corrode on the inside, where alloy was flowing, because the temperature of flowed LBC was 250 °C, corrosion could not develop at such temperature. However, when materials engineers examined those tubes, they saw corrosion cracking caused by chlorides and oxygen and that was typical for austenitic steels.**

## *2.3 Coolant Leaks (5)*

- **Of course, there was oxygen inside the tight compartment as there was air. The question was about chlorides. How did they arise? The facilities were constructed in short terms, i.e. very quickly. The heat-insulation used in heat-and-power engineering, boiler engineering was selected. However, when that heat-insulation was subjected to chemical analysis, it turned out that it included sodium and magnesium chlorides. In case it was dry and hot, no problems arose. Development of corrosion required existence of chlorine ions, i.e. those salts had to be dissolved.**
- **Examination of the steam heating pipelines revealed the following. Due to the narrowness of the compartment, it was difficult to control weld seams. The certain space was required to place an X-ray film, instrumentation and so on. All weld seams over the primary circuit were thoroughly controlled with X-rays. However, regarding to the weld seams of the steam heating pipelines, it might seem that their exposure to irradiating by X-rays was not needed.**

## *2.3 Coolant Leaks (6)*

- **But, it turned out that several tubes in the steam heating system were steam-leaked. However, the cold surfaces existed in the same bulk, as they were cooled by water. The steam penetrated there very slowly, then it was condensing on cold surfaces somewhere on top. Condensate drops fell down on heat insulation and were saturated with chlorides. Then the water with chlorides dripped on the pipelines. That was the reason.**
- **Later the similar emergency situation was developed at the pilot NS of Project 705 (Order 900). However, it was impossible to do anything. The NS had been standing in building berths with a mounted reactor compartment. Otherwise, the RF had to be decommissioned. The question regarding to further events at the NS arose. Everybody understood that in an event of steam ingress, the emergency situation would be developed. For that reason, the operation of the NS of Order 900 was shutdown prior to the appointed time.**

## 2.3 Coolant Leaks (7)

- **The indicated heat-insulation is applied in heat-and-power engineering (even if it is wet) because black carbon steels are used. Those steels are subjected to general corrosion, i.e. rusting. However, in carbon steels there is no corrosion cracking caused by chlorides and oxygen. Therefore, in heat-and-power engineering such heat-insulation operated perfectly. I.e. it was incorrect to use experience gained in heat-and-power engineering without account of differences in the applied materials.**
- **In the course of repair and maintenance works at Facility 27/VT the corroded pipelines were replaced, newvelevaya heat-insulation was replaced by asbestos one with normalized content of chlorides. To control each weld seam on tubes of the steam heating system was very difficult and it could take a long time, but that problem was solved as well.**
- **The repeated launchings of the facility revealed that in the course of performance of repair works not all pipelines with chloride corrosion were replaced. That fact was taken into account and required realization of total renovation of the system of primary circuit auxiliary pipelines.**

## *2.3 Coolant Leaks (8)*

- **The repair works and elimination of consequences of leak in the primary circuit system were entirely finished by the middle of March, 1960, i.e. they took approximately a year for their realization.**
- **Further, the reactor facility operated without corrosion problems on the outside. The recommendations for NSs were made.**
- **Regarding that accident, Academician A.P. Alexandrov, who was a Chief Manager of all works concerning the NSs in the USSR, said that experience gained due to the happened accident helped us very much. At that time the reactor facility at Soviet nuclear-powered icebreaker "Lenin" was being mounted with similar heat-insulation. Based on the gained experience, and with a little delay in construction, the heat-insulation without chlorides was mounted at nuclear-powered icebreaker "Lenin".**

# *2.4 Polonium Exhaust (1)*

- **In the process of works on replacement of tubes the second phase of the real adventure story started. It was the first experience in performance of welding works on pipelines with flowing inside coolant that contained polonium. No special measures were taken except for protection of the welder's respiratory organs by a respirator. The bellmouth was installed in the exhaust ventilation for the purpose not to release the "dirty" air in the central room, and the welder began to perform his work. In several minutes everybody could hear the dosimetric signaling alarm in the central room.**
- **All works were terminated at once, because in the air of the central room there were 14000 of ultimately permitted concentrations of polonium aerosols. At the meeting held by A.I. Leypunsky in his working room D.M. Ovechkin, who was Chief Engineer of IPPE, said that "it was the last nail in the cover of the coffin for that trend". Later, the group of specialists including D.M. Ovechkin was given the Governmental Award.**

## *2.4 Polonium Exhaust (2)*

- **The reason was in the following. When fired works were performed, even an eye-invisible film, surface contamination containing polonium would sublimate at once. The developed instruction involved the following order of realization of works: first, to strip each surface "in the cold state" to the luster, then wipe it with the help of a spirit tampon and dry. Then one should take a smear and give it to dosimetrists for examination of alpha-activity. In case the dosimetrists found the alpha-activity to be within a permitted range, one should perform welding.**
- **When the specified order of activities was adhered, the dosimetric situation became normal, and all new auxiliary pipelines of the primary circuit were welded.**

## *2.4 Polonium Exhaust (3)*

- **As for the people health, there were no consequences because polonium aerosols were short-lived. They precipitated on the walls and flour very quickly, i.e. self-refining of air was realized. In twenty-four hours there was very little precipitation on walls and the air was clean. However, the personnel who worked in that building, came and worked in their own clothes and shoes. Then they went home.**

- **It was clear that the people, who performed those works and left the building, were contaminated with polonium. The dosimetrists followed them with dosimeters (similar to following with mine-detectors). Their devices were very sensitive, in fact, they could count every alpha-particle. When they came to the flats of the worked personnel, they asked them to give away their "dirty" (contaminated) shoes. So, that was an episode in the process of mastering of that technology.**

## *2.5 Incidents at the Secondary Circuit Equipment (1)*

- **In each steam-turbine installation there is a bypass pipeline of fresh steam with an etching valve. In case, for the certain reasons the turbine cannot intake steam, an etching valve is opening, and over that pipeline the steam is passing past the turbine straight to the condenser.**
- **For the purpose to perform that operation without exceeding of pressure and actuation of safety valves for steam discharge into the atmosphere, at Facility 27/VT there was a mechanical device that provided opening of the etching valve, i.e. steam discharging in the condenser, in case the valve for steam insertion in the turbine (maneuvering valve) was closed. I.e., the steam flow was switched over. At that point, for the purpose to lower the temperature and steam pressure in the condenser, the water was injected into the steam flow incoming in the condenser.**

## 2.5 Incidents at the Secondary Circuit Equipment (2)

- However, in the indicated device the manual switching off of that blocking was provided and used in the process of debugging. In the process of operating at power the operation of valves should be performed in the following order: the first valve was opening, the second valve was closing. Of course, in the process of operating at power the etching valve was closed, otherwise it was a bypass, i.e. idle loss of power, as the certain part of steam was going past the turbine.
- However, due to the unascertained reasons, it turned out that in the process of operating at power, there was no indicated blocking, and the valves were managed independently of each other. I.e. the initial state was as follows: the valve for steam insertion in the turbine was open, the valve for steam discharge in the condenser was closed. Something happened at the turbine. There were many signals, which protected the turbine against exceeding of the number of revolutions, the hydro-brake that simulated a load on the NS screw propeller and so on. As a matter of fact, the valve for steam insertion in the turbine was closed, the valve for steam discharge in the condenser was not open because there was no blocking.

## *2.5 Incidents at the Secondary Circuit Equipment (3)*

- **The reactor power was 60 % of the nominal one. At the moment, when the valve for steam insertion in the turbine was shut in, the steam pressure increased sharply.**
- **At each LBC cooled RF the steam generator in the secondary circuit is divided in two parts, namely: the evaporator, in which the multiple forced circulation (MFC) pumps are purging the boiler water, and at the outlet the steam-water mixture is formed; then it is transferred to the separator, where it is separated into dry saturated steam and water under boiling point (separate). In the steam over-heater the saturated steam is overheated.**
- **When steam pressure increased, even prior to actuating of safety valves, the temperature of water boiling increased, in the evaporator the heat removal deteriorated sharply because it was realized mainly due to latent heat of steam generation. Only further, the safety valves actuated.**

## *2.5 Incidents at the Secondary Circuit Equipment (4)*

- **As a result of deterioration of heat removal in the SG, the LBC temperature at the reactor outlet increased sharply that caused actuation of emergency protection (EP) of the reactor, which was realized with a certain delay.**
- **In addition to the logger that registered steam pressure, there was a logger that registered the coolant temperatures at the reactor inlet and reactor outlet. On the tape of recording of LBC temperatures at the reactor outlet, one could see that almost at once (for 1-2 seconds) the LBC temperature increased by 100 degrees, then it began to decrease after actuation of the EP system.**
- **Nevertheless, nothing was damaged. For example, in case the volumetric expansion coefficient in the primary circuit coolant was high, i.e. such as that in water, the pressure surge in the primary circuit could cause damage in the circuit (we are addressing the natural properties of coolant.**

## *2.6 The First Phase of the Real Adventure Story of SG Leaks (1)*

- **Construction of ship RFs with lead-bismuth coolant required development of the number of mechanisms and equipment, which differed from those ones used earlier both in the traditional power and in the RFs with other coolants.**
- **Those equipment included the SGs with multiple forced circulation of water in the secondary circuit, which provided generating of over-heated steam.**
- **The first LBC cooled RFs, namely: Facility-prototype 27/VT and the NS of Project 645, were equipped with single-type SGs: MP-1 and MP-2. As their operation revealed, the lack of experience in development of the equipment for those facilities caused the certain structure drawbacks in the SG design.**

## *2.6 The First Phase of the Real Adventure Story of SG Leaks (2)*

- **Each of three sections of MP-1 and MP-2 (they were identical) was made of stainless steel of the austenitic class and shaped as a cylindrical vessel with a sphere bottom and a tube plate welded on top.**
- **The heat exchange surface was made as a cluster of U-shaped tubes with beading and welding of their free ends in the tube plate. The LBC was purged over the inter-tube gap, steam and water were purged over the tubes. To organize the required direction of coolant flowing along the tubes, the cylindrical dividing plate was mounted inside the SG vessel. It provided dividing of the inter-tube gap into evaporator chamber and over-heater chamber.**
- **From the reactor the LBC was transferred to the outside circular chamber of the inter-tube gap and sank to its bottom part with washing of over-heater tubes. Then it was transferred up over the inner cylindrical chamber of the SG, where the evaporator tubes were installed. After escaping from the SG, it was transferred to the pump suction in the primary circuit.**

## 2.6 The First Phase of the Real Adventure Story of SG Leaks (3)

- The evaporator and over-heater tubes were spaced with the help of special grids made of steel plates. On the tube plate there was mounted a cylindrical course with steam-water chambers, which were covered by an intermediate and power lids with sealing gaskets. The removable lids provided an opportunity of free access to the tube plate for the purpose to detect and plug the leaked tubes.
- Operation of both RFs was followed by frequent failures of inter-circuit tightness in the points of embedding of tubes in the SG tube plate that was caused by high temperature irregularity in the tube plate, which was a result of mounting of the over-heater and evaporator in the same vessel and undeveloped technology of sealing of tube clusters in the tube plates.

## *2.6 The First Phase of the Real Adventure Story of SG Leaks (4)*

- **In certain situations the value of leak was 120-150 kg/day.**

**The technological schemes of the primary circuits of all RFs of NSs with LBC and their prototypes provided the opportunity to indicate the leaked section in the SG for any heat-exchange loop of the reactor.**

- **Renovation of tightness in the tube system at the SG section withdrawn from operation was obtained by mounting of plugs in the leaked tube from the side of steam/water inlet and outlet and welding of plugs in the tube plate. Such repair work could be realized without any difficulties, as the temperature of the tube plate was not higher then 160-180 °C, and at the NS of Project 645 it was possible to perform repair work even in the sea.**

- **Frequent leaks in the evaporator tube system of all three sections in the SG of Facility 27/VT, which arose over embedding of tubes in the tube plate, resulted in the necessity to terminate testing for the purpose to perform repair works and also caused LBC ingress in the SG chamber in the secondary circuit in events of personnel's erroneous actions performed for the purpose to detect leak. That required to remove LBC, and then perform decontamination.**

## *2.7 Fuel Unloading (1)*

- **The operation on fuel unloading, in which the whole core was removed, was performed for the first time. The specialists of EDO “Gidropress” designed a protective cask for refueling works, which included a winch with an engine. The whole removable part of the reactor together with a core was drawn into that cask by a winch.**
- **The residual heat release was removed by air. For that purpose, in the upper part of the cask the corrugated flexible rubber-metal hose pipes were mounted and connected to the box of the exhaust system of special ventilation. The pure air was sucked in the cask from the bottom and cooled the core. The crane lifted that cask, transported it to the place in the central room, where the storage was installed, and lowered. Then, with the help of the winch the removable part was put into the storage, the cask was put on its place and the storage was covered by the coverage. The cooling system was used there as well.**
- **Because the cask was open from the bottom for intake of cooling air, everybody understood that in the process of cask transportation the coolant would drip on the floor.**

## *2.7 Fuel Unloading (2)*

- **That was why prior to transportation of the cask by a crane, a time lag of approximately 30 minutes was provided for draining of the alloy bulk from the removable part into the reactor vessel. In addition, over the route of cask movement the elastron roll was laid for the purpose to eliminate contamination of the floor. All lead-bismuth drops, which dripped on the elastron roll, were collected (their total amount was less than the volume of the cup). Then together with the elastron roll they were thrown down to the solid waste storage. In three years, there were virtually no polonium.**
- **The unloading procedure went off smoothly though there was a certain misgiving. The misgiving was caused by the fact that the effect of fast neutrons could cause embrittlement in the ferrite-martensitic steel of the fuel elements cladding in the bottom "cold" part of the core. For that reason, the materials technologists proposed to renew plasticity of steel EI-852 (ЭИ-852) (advanced steel EP-823Sh (ЭП-823Ш) was mastered much later) by performance of high-temperature annealing of radiation defects. Today such annealing is periodically realized at every vessel of VVER type reactors as they are subjected to embrittlement as well. However, that time it was carried out for the first time.**

# *2.7 Fuel Unloading (3)*

- **For that purpose the bypass valves in the course of the reactor removable part were opened. Those bypass valves provided short closing of the coolant flow inside the reactor, namely: hot coolant from the core was going up and if the valve was open, it penetrated to the downcomer section where the cooling channels were mounted.**
- **When annealing was performed, the cooling of cooling channels was switched off. The established power of reactor operation was small, such as 100-200 kW, and the natural circulation of LBC was realized due to its cooling via the reactor vessel with discharging of heat into the water-lead protection tank. At that point, the LBC temperature at the inlet increased to 450 °C, when annealing was being realized and plasticity of steel was partially renewed.**
- **Those valves were not provided for annealing, but for reactor cooling in an event of loss of the opportunity of cooling via the SG. In the period of development of the Project, the effect of low-temperature radiation embrittlement of steels was unknown.**

## *2.8 The Second Phase of the Real Adventure Story of SG Leaks (1)*

- **The second lifetime of Facility 27/VT provided not only development of the new core design, but testing of the new advanced steam generators. For that purpose, section MP-7 of the SG, which was an analog of steam generators at the RF of Project 705 NS, was installed at the Facility.**
- **The whole steam generator was made of pearlitic class steel that was corrosion resistant to corrosion cracking in presence of chlorides and oxygen in water and corrosion resistant to LBC as well. The SG was a tubular heat exchanger fabricated in a form of two U-shaped vessels mounted in sequence on a single baseplate. From the reactor the LBC flowed sequentially to the inter-tube gap of the steam-overheating and evaporating SG sections. Then LBC flowed to the inlet of the main circulation pump in the primary circuit.**

## *2.8 The Second Phase of the Real Adventure Story of SG Leaks (2)*

- **The tube clusters were also made as U-shaped tubes beaded and welded in two tube plates of each section. Spacing of tubes in the tube cluster was realized with the help of lamellar grids in several points over the height of cylindrical parts of the sections.**
- **Over the inter-tube gap (the primary circuit) two vessels in the upper part were joined together by a transition chamber. The cylindrical chambers of boiler water and steam-water mixture were installed on the vessel of the evaporating section above the tube plates. The chambers of saturated and over-heated steam were mounted on the vessel of the steam-overheating section. All steam-water chambers were sealed by removable lids on nickel-base gaskets that provided the access to the tube plates when repair works were performed at the SG.**

## *2.8 The Second Phase of the Real Adventure Story of SG Leaks (3)*

- **Testing of section MP-7 of the SG revealed that the design required serious re-development both in the part of technology of tubes sealing in the tube plates because of frequent leaks in the points of tube embedding, and in the part of heightening of stiffness of tube cluster spacing. The infrequent leaks in tubes in the points of their embedding into the tube plates did not cause much problems during the operation because the technology of repairing of SGs by plugging of leaked tubes had been mastered. However, the problem of insufficient stiffness of tube spacing was very serious.**
- **The significance of the highlighted problem became clear when in the process of testing the systematic leaks in the evaporating SG section arose. As compared with that of the over-heating section, the length of the evaporating section was larger that resulted in the lower own frequency of oscillations. Because of the systematic character of leaks, their reason had to be determined and eliminated. The whole burden of that complex work fell on the designers of EDO “Gidropress”, who were maintaining the operation.**

## 2.8 The Second Phase of the Real Adventure Story of SG Leaks (4)

- **First, it was revealed that leaks were not developed over the points of tubes embedding into the SG tube plates, but they were developed somewhere over the tube length. Second, with the help of special devices and techniques the distance from the tube plate to the point of tube leak was determined.**
- **It turned out that in all leaked tubes the point of leak was at the same distance from the tube plate. When that distance was marked on the drawing, it became clear that it coincided with the point of arrangement of spacing bars. That information was horrified because it meant that the SG design had to be changed due to impossibility to replace the spacing bars.**
- **That assumption was considered prior to the moment when designers of EDO “Gidropress” found the solution to the stated problem. With the help of a specially made instrument they managed from the tube inside (the tube diameter was 8 mm) to cut off the tube in the end of the straight section in the point where bending was beginning. Then they drilled the welded seam and removed the specified tube fragment from the SG.**

## *2.8 The Second Phase of the Real Adventure Story of SG Leaks (5)*

- **After that everything became clear because in the points where the spacing bars were mounted the cylindrical tube, which wall was 2 mm in width, became six-sided like a pencil. The vibration of tubes resulted in their mechanical wear in the points where the tube wall touched the spacing bars installed in three tiers over the height with formation of a six-sided cell.**
- **How could it happen? The vibration tests performed at the SG model with the less number of tubes and under velocities of coolant flowing, which were within the design basis, revealed the absence of vibration wear of tubes.**
- **The analysis of the obtained results and conditions of test performance at the SG model and mockup showed that the striking difference in the results was caused by a scale factor, which was always difficult to account when the results of testing at the reduced model of the equipment (of course, that was cheaper and faster) were applied to the mockup.**

# *2.8 The Second Phase of the Real Adventure Story of SG Leaks (6)*

- **The heaviness of that situation consisted in the fact that the same problem was in each of seven NSs of Project 705 (705K), which had been standing in building berths of two shipbuilding yards in high readiness with mounted reactor facilities.**
- **However, nobody had the courage to pose for the decision-making authorities the question concerning the immediate termination of construction of the whole NS series, development of renovated SGs, manufacturing of renewed SGs and replacement of the already assembled SGs by the new ones at every NS. That decision was made after performance of tests and completion of experimental operation of the pilot NS of Project 705 (Order 900), which results were crucial for serial NSs.**
- **The representative tests of the upgraded SG mockup with MP-7M with renewed spacing bars, designed by the specialists of EDO "Gidropress" were performed at a special facility of OKBM (now it is Joint Stock Company "Afrikantov Experimental Design Bureau for Mechanical Engineering" (JSC "Afrikantov OKBM")) and revealed the total absence of vibration wear of tubes. Moreover, a new method of tubes sealing in the tube plates was implemented in the technology of manufacturing of the renovated SGs.**

# Conclusion (1)

1. Development of RFs with LBC was realized in conditions of absence of necessary knowledge and experience. Moreover, the fixed directive terms of work completion practically eliminated the opportunity for performance of related scientific and research works that caused a number of failures at the stage of mastering of that technology.
2. In the process of test performance at Facility 27/VT the invaluable experience was gained, which made possible elimination of the reasons of the accidents happened at RFs of serial NSs of Project 705 (705K) and provide their reliable operation.
3. The values of characteristics obtained in the process of RF testing and operating, namely: capacity and parameters of the facility, duration of lifetime, reactivity margin, reactivity coefficients, poisoning effects, temperature distributions, dynamical parameters, radioactivity of coolant, neutron and gamma-radiation dose rates beyond the protection agreed sufficiently well with those in the computation results.

# Conclusion (2)

4. When repair works and unloading of the reactor were realized, it was not required to perform decontamination in the primary circuit, which was coupled with collection, storage, transportation and reprocessing of large amount of liquid radioactive waste (LRW).
5. The opportunity of RF operation in an event of small leak in the SG tube system was verified. High repairability of the SG, the opportunity of stable RF operation at any low power levels were confirmed as well. Storage of unloaded spent removable parts of the reactor realized in the “frozen” coolant assures nuclear safety and eliminates formation of LRW.
6. On the basis of critically analyzed operating experience, the development of the RF Project for civilian purposes (SVBR-100), which is meeting the Generation IV requirements, is carried out.

THANK YOU VERY MUCH

FOR YOUR ATTENTION

# History of Pb and Pb-Bi Heavy Coolant Technology Development

## SSC RF – IPPE - THE BIRTHPLACE OF Pb AND Pb-Bi HEAVY COOLANTS

**Yu.I. Orlov**

**SSC RF – IPPE**

**Obninsk**

October 2018

# HISTORY OF HLMC

- After the war, the submarine shipbuilding was adopting nuclear power.
- Search for the most promising areas for nuclear marine propulsion plant (NMPP) development was underway.
- The following two alternative options were considered to be the most problematic:
  - water-cooled plant;
  - liquid-metal cooled plant.

# BACKGROUND

In October 1949, A.I. Leypunsky posed the question of the development of fast and intermediate-neutron power reactors with liquid metal coolant in the IPPE.

For submarine reactors A.I. Leypunsky suggested the use of lead-bismuth eutectic as a coolant.

A.I. Leypunsky’s choice of lead-bismuth eutectic was determined by good physicochemical and thermophysical properties of the alloy.

# LEAD AND LEAD-BISMUTH COOLANT ADVANTAGES

- **Low chemical activity of lead and bismuth in the event of interaction of the alloy with air, water, vapor rules out the possibility of explosion and fire.**

- **High boiling point of the coolant (Pb - 1737$^{O}$C, Pb-Bi - 1670$^{O}$C) rules out the possibility of its boiling in energy-intensive areas of the plant.**

- **Low operating pressure in the coolant circuit improves reliability, safety, simplifies the design and production of equipment, substantially alleviates reactor equipment operation conditions.**

# HEAVY COOLANT DEVELOPMENT STAGES

**1950 – beginning of work on substantiation of nuclear power plants with lead-bismuth coolant.**

**1951 – creation of the first circulation liquid-metal test facility with lead-bismuth coolant.**

**1951-1968 – construction of the research and test facilities in IPPE, CKTI, CRISM "Prometey", MO CKTI, OKB Gidropress, OKBM.**
**Studies on Pb-Bi alloy as a coolant were reported to be carried out in the USA and Canada.**

**1959 – power start-up of the on-shore prototype – nuclear power plant with Pb-Bi alloy – 27/Vt test facility.**

# NUCLEAR SUBMARINE (NS)
# PROJECT 645

- **The activities on the design of the first NS (Project 645) with liquid metal Pb-Bi alloy began in SKB-143 in 1952.**
- **A.K. Nazarov became the chief designer.**

**Scientific supervision was carried out by A.I. Leypunsky.**
**The chief supervisor was A.N. Donchenko – Engineer Captain I-st rank, the only woman who ever held a similar rank.**

- **OKB "Gidropress“ was directly involved in steam generating plant (SGP) development under the direction of B.M. Sholkovich.**
- **Since 1972 scientific supervision was carried out by B.F. Gromov.**

# Nazarov Aleksandr Karpovich

Chief Designer of NS Project 645

# Donchenko Aleksandra Nikolaevna
## Chief Supervisor

# Sholkovich Boris Mikhailovich
# NS Chief Designer

# Gromov Boris Fedorovich

# NS “К-27”

# Gulyaev Ivan Ivanovich
## The first captain of the "К-27" nuclear submarine

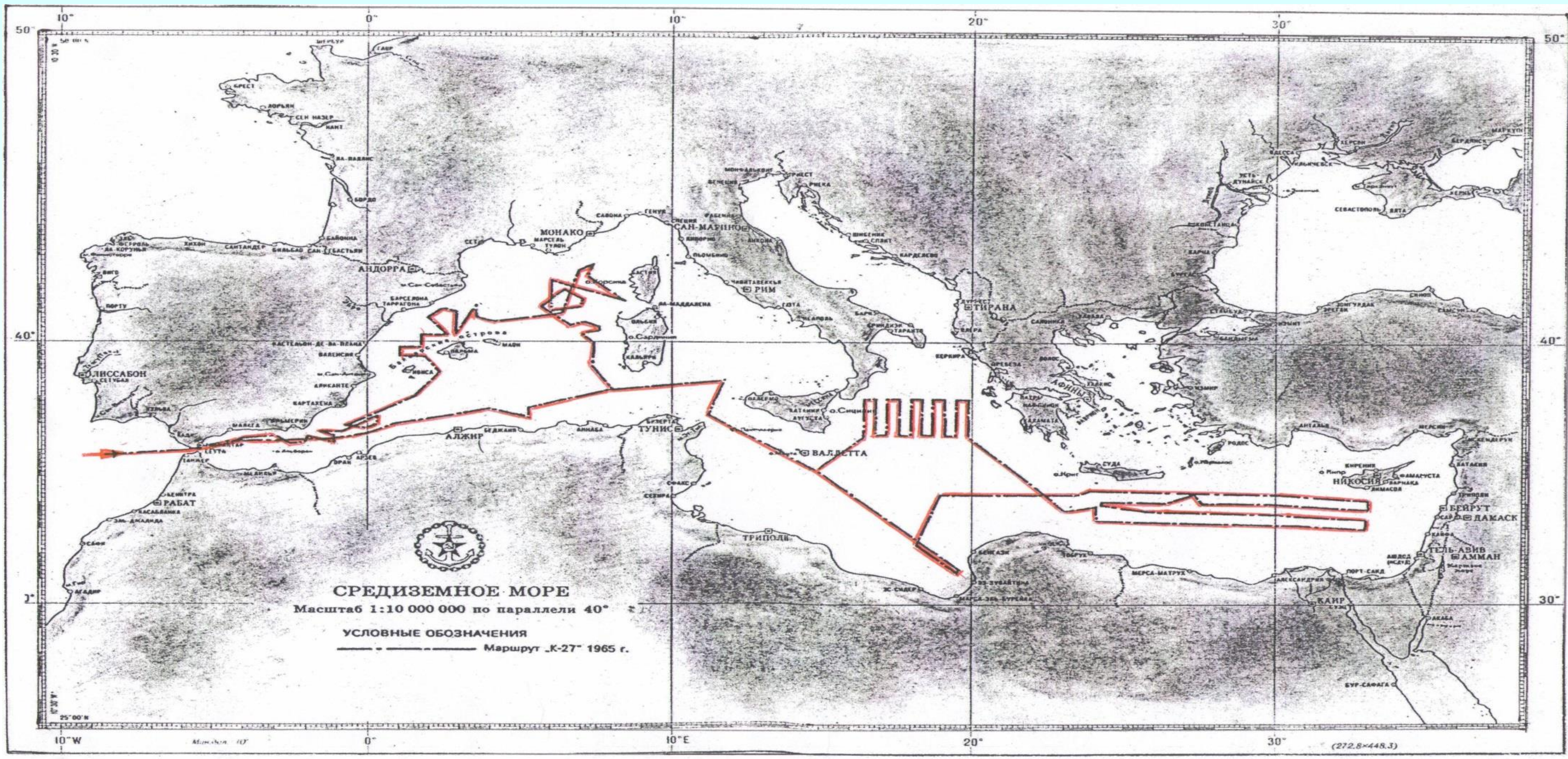
# FIRST CRUISE OF NS “К-27”

- In 1963 NS “К-27” was commissioned.
- In the first cruise the K-27 submarine spent 51 days, covered 12425 miles (of which 12289 miles - 89% under water).
- In the course of the cruise the power plant demonstrated stable operation in all latitudes, including equatorial ones.
- The results of this cruise further strengthened the sailors' confidence in <u>high reliability and safety of liquid metal cooled SGP.</u>
- It was the first fully autonomous cruise of the Soviet ship.
- <u>And it was a world record of continuous submergence.</u>

# SECOND CRUISE OF NS "К-27"

- The second cruise of the submarine took place in autumn 1965 and lasted 60 days - from July 15 to September 13.
- was to indicate the presence of the Soviet submarine fleet in The cruise mission the Mediterranean.

## «К-27» Route



## ACCIDENT

- In early 1967, the cores were refueled, and preparations were being made for combat readiness exercises.
- But the submarine was not ready. The required pre-cruise works had not been fully performed.
- However, under the pressure of “high" command on May 21, 1968, the K-27 submarine put out to sea to exercise combat tasks.
- On May 24 around 12-00 as the plant was brought to the full-speed mode, a portside reactor accident occurred.

- **In early June, 1968, the submarine was examined by a special commission that came to the conclusion on the necessity to cool down the reactors and solidify the alloy in the reactors from both sides.**
- **It was considered a death sentence for K-27 – it was practically next to impossible to put the reactors back in operation after the eutectic solidification.**
- **The commission had to take that forced step because of the severe radiation situation still in place on board.**
- **However, a few years later, the scientists managed to recover the surviving reactor and increase its power up to 20%. But at the time when the decision was made, nobody knew about that feasibility, <u>about incredible survivability of reactors with heavy liquid metal coolant.</u>**

- **The feasibility to recover the operation of reactor circuits with HLMC after its solidification was demonstrated. A cycle of work was performed on low-temperature reduction of lead oxide by hydrazine-hydrate in the primary circuit.**
- **For the first time, the coolant purification method developed at the IPPE was tested at the “К-27” submarine through non-stop injection of helium-hydrogen mixture by means of a special ejection device.**
- **The coolant purification system demonstrated reliable and efficient operation. The possibility to continuously maintain the process in the course of NPP operation was experimentally confirmed.**
- **The experience of operation of the system for continuous purification of the circuit and alloy from slags (Order 601) was recommended to be used in the orders under Project 705.**

# PRINCIPAL TASKS FOR HEAVY COOLANT TECHNOLOGY

- **During that time the work was already under way to develop and construct nuclear submarines under Projects 705 and 705K.**
- **After the accident, it became obvious that it was necessary to solve two principal tasks with the aim to ensure a long-term accident-free operation of the plants with Pb-Bi coolant:**

1. **To provide a required level of purification of both the coolant and inner surfaces of the equipment in the circulation circuit.**

2. **To provide corrosion resistance of structural materials used in contact with the alloy.**

- **In order to solve these tasks, in Russia (primarily at the IPPE) an expanded program was launched with the aim to study Pb-Bi alloy properties, physical and chemical processes and thermal hydraulics in non-isothermal circuits, corrosion resistance of structural materials, impurity sources and their impact on the plant operability.**

- The work on development of heavy coolant technology and research into circuit thermal hydraulics was entrusted to the team of specialists under the supervision of V.I. Subbotin, and since 1975, P.L. Kirillov.
- A large experimental base was set up; it included dozens of circulation facilities.
- Hundreds of specialists were involved.

At the IPPE first a laboratory and then a division were established with the aim to study and develop a heavy coolant management technology.

**Subbotin**
**Valery Ivanovich**

**Kirillov**
**Pavel Leonidovich**

# Laboratory 100, the year of 1974

# THE RESULTS OF WORK WITH Pb-Bi ALLOY

As a result of that work, the following tasks were solved:

- scientific fundamentals were developed for Pb-Bi coolant management technology;
- special methods and devices for purification of coolant and circuit surfaces from impurities were developed;
- methods and devices were developed to control Pb-Bi alloy quality;
- methods and devices were developed to maintain the optimum quality of Pb-Bi alloy, which could provide the adequate corrosion resistance of structural materials.

# MAIN SOLUTIONS THAT ALOWED THE LEAD-BISMUTH COOLANT TECHNOLOGY TO BE SUCCESSFULLY DEVELOPED

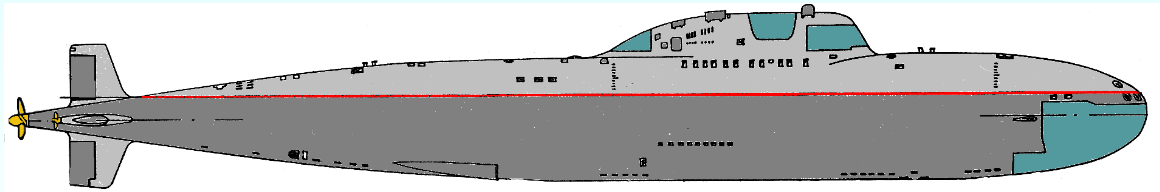
1. Selection of oxygen technology to protect structural materials.

2. Development of the method to purify the alloy and circuit from impurities with a two-component flow "alloy-gas".

3. Development and implementation of sensors to measure oxygen thermodynamic activity in the alloy.

**1976 – the first regulatory document on Pb-Bi coolant technology called "Guidance on Nuclear Submarine Coolant Management Rules" was developed and implemented.**

**1977-1981 – six nuclear submarines, Project 705(705K), with nuclear reactors cooled with lead-bismuth were commissioned.**



**Nuclear submarine**
**Project 705 ("ALFA")**
**Displacement 3600 t**
**Dimensions 81.4 × 9.5 × 7.6 m**
**Submergence depth up to 320 m**
**Speed up to 41 knots**

# NEW COOLANT TECHNOLOGY TASKS

**For nuclear power plants of the new generation (BREST, SVBR), there appeared the factors that determine new tasks pertaining to heavy coolant technologies:**

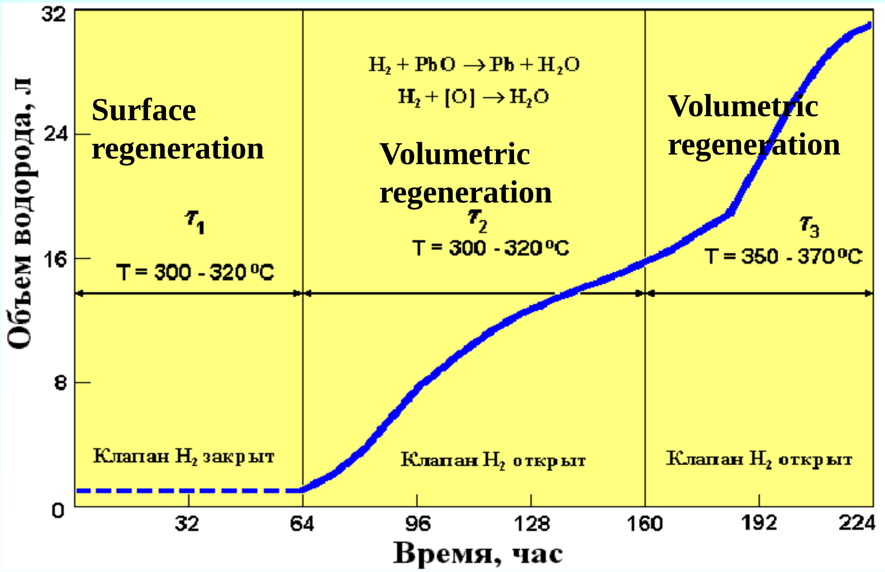
- **Scale**
- **Configuration**
- **Operating parameters**
- **Life time**

**To some extent, these factors hamper implementation of the coolant technology processes.**

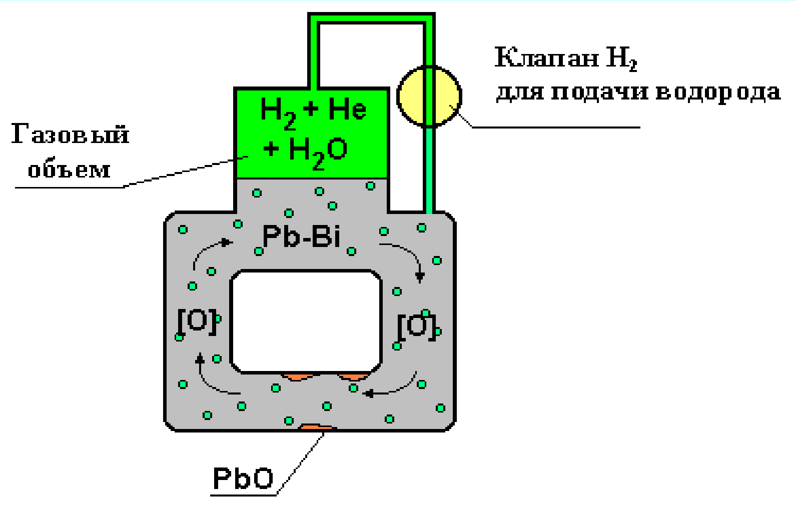
**1988 – the beginning of intensive lead coolant studies and start-up of the first lead circulation facility.**

# COMPREHENSIVE STUDY OF HYDROGEN PURIFICATION OF CIRCUITS FROM LEAD OXIDE-BASED IMPURITIES

$$(H_2) + \langle PbO \rangle \rightarrow (H_2O) + [Pb]$$
$$(H_2)+[O] > \rightarrow (H_2O)$$

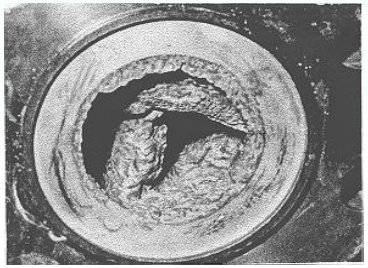



Efficiency of circuit hydrogen purification

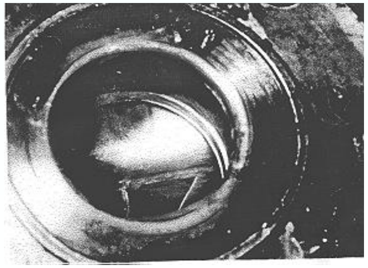



Facility diagram

## Interaction with hydrogen-helium mixture



"Dirty" section of the circuit before purification



The same section after purification

# DISSOLVED OXYGEN CONCENTRATION CONTROL IN Pb-Bi ABD Pb COOLANTS

**The following processes are used to control the dissolved oxygen concentration in the coolant::**

- **supply of gaseous oxygen in to the circuit;**

$$O_2 + PbO \rightarrow 2 < PbO >$$

$$< PbO > \rightarrow Pb + [O]$$

- **coolant oxidation by mixtures of $H_2O$ and $H_2$**

$$H_2O + Pb\,(Pb - Bi) \rightarrow Pb\,(Pb - Bi) + [O] + H_2;$$

- **dissolution of solid-phase lead oxide (PbO) in the coolant.**

$$< PbO > \rightarrow Pb + [O]$$

# FILTRATION OF THE COOLANT

**At this point, comparative testing has been performed of a wide range of filter media to purify coolants from suspended impurities: glass fiber, carbon fiber, needled fabric from metal fiber, $Al_2O_3$ granules and others.**

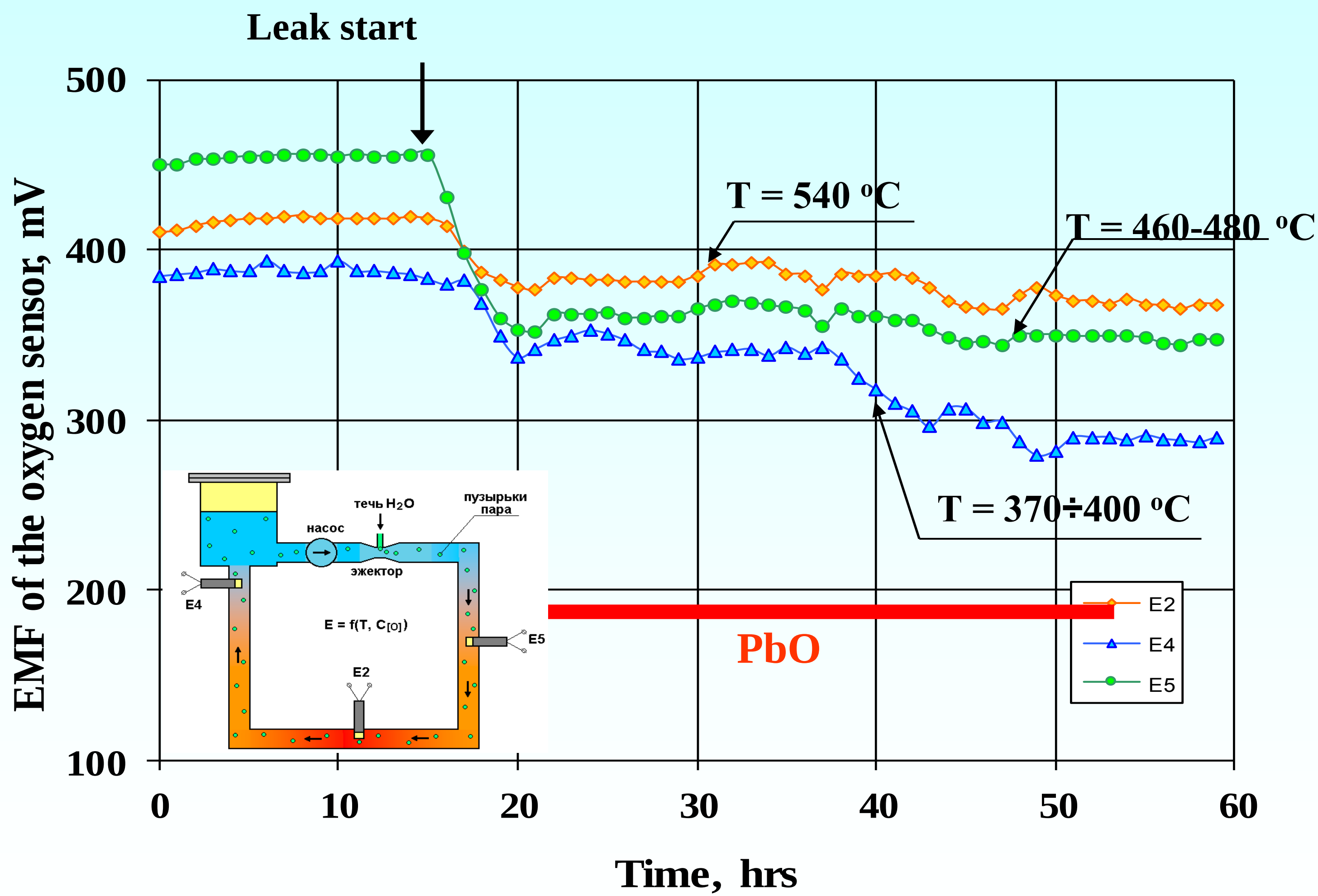
**Taking into account the operation conditions of the reactor units with heavy coolants, needled fabric from metal fiber and $Al_2O_3$ granules can be recommended for further testing.**

# IMPACT OF STEAM GENERATOR LEAK ON THE COOLANT TECHNOLOGICAL PARAMETERS

- **Experiments were performed in non-isothermal mode ($t_{min} \approx 400$ °C, $t_{max} \approx 540$ °C) of circuit operation.**

- **Upon coolant exposure to water steam (total experiment time > 300 hours), very low oxidation of the melt is observed, which is manifested in certain increase of thermodynamic activity and, therefore, oxygen concentration in the coolant. Oxygen sensor readings are stabilized at the level $a = 10^{-4} – 10^{-3}$.**

# SIMULATION OF THE STEAM GENERATOR LEAK AT THE TT-2M FACILITY (Pb-Bi, $T_{max}$ ~ 540 °C, $T_{min}$ ~ 400 °C, leak = 14 g/h)



# DISSOLVED OXYGEN ACTIVITY SENSORS

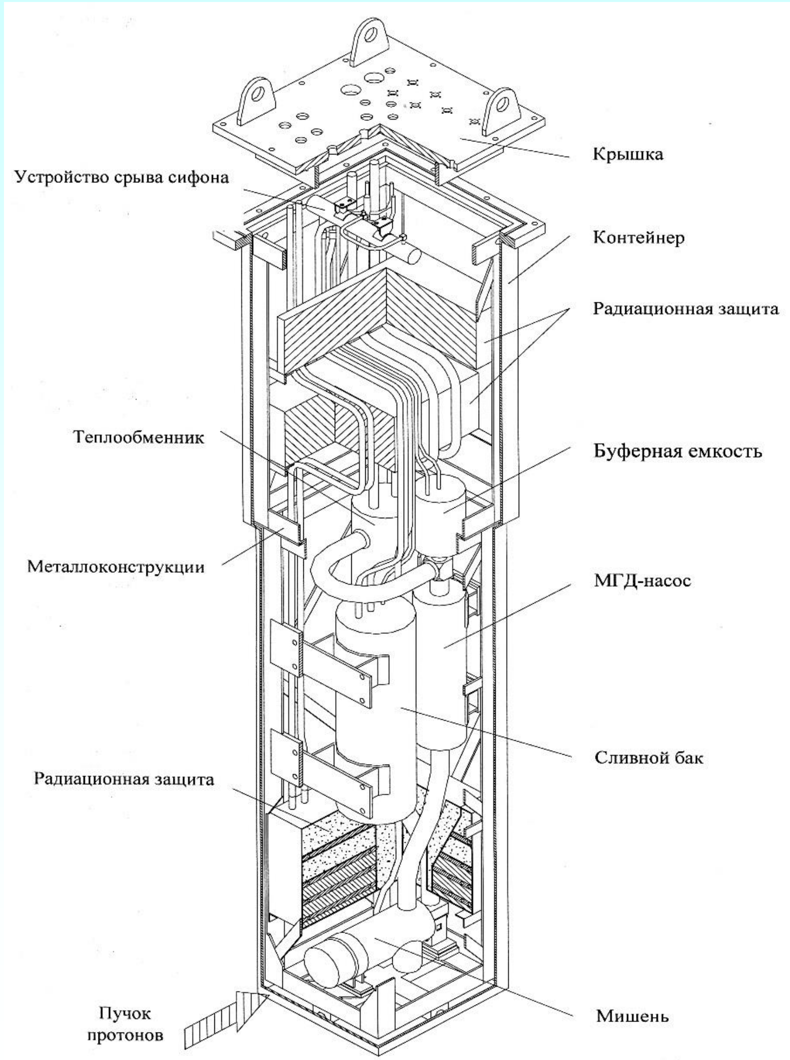
# TARGET

**In the end of 1990s, it was suggested by Nobel Prize winner Karlo Rubbia to create accelerator-driven systems with Pb-Bi. IPPE took an active part in this work.**

The year 1997

**In cooperation with OKB "GIDROPRESS", the first in the world target MK-1 was created in IPPE for application in accelerator driven systems.**

## MK-1 DESIGN



# MK-1 FORMING PART OF A TEST FACILITY IN LAS-VEGAS, 2004

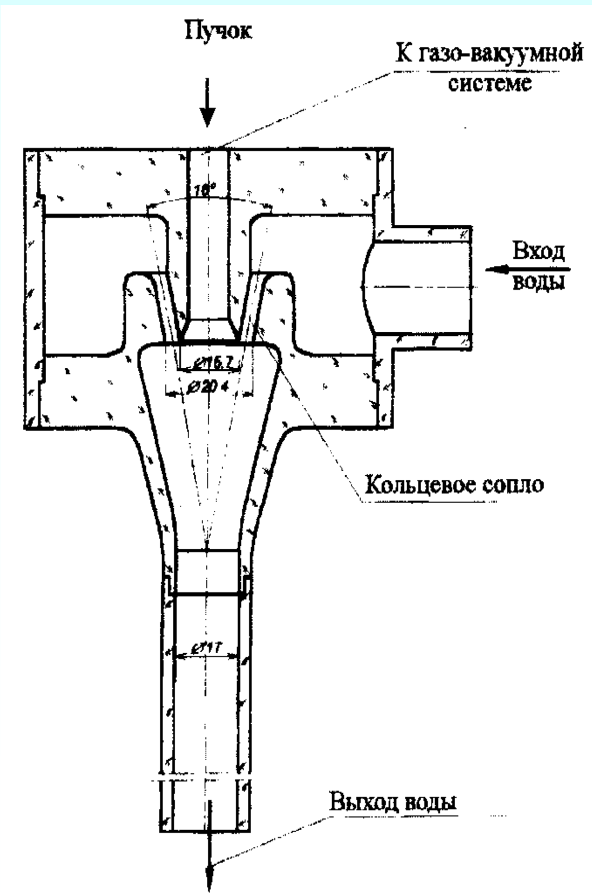
# "WINDOWLESS" TARGET

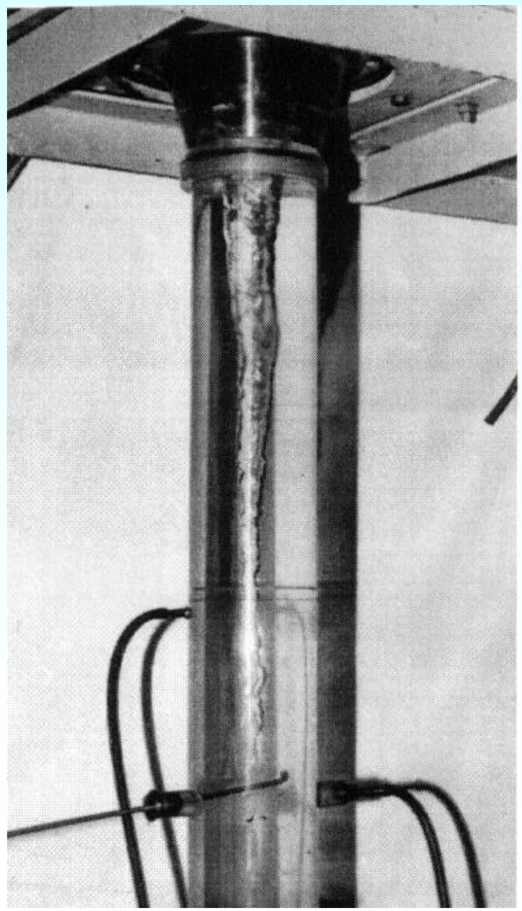
- **Active part of the target, which is a critical component of the liquid-metal circuit, can be considered in two variants: with and without the diaphragm.**

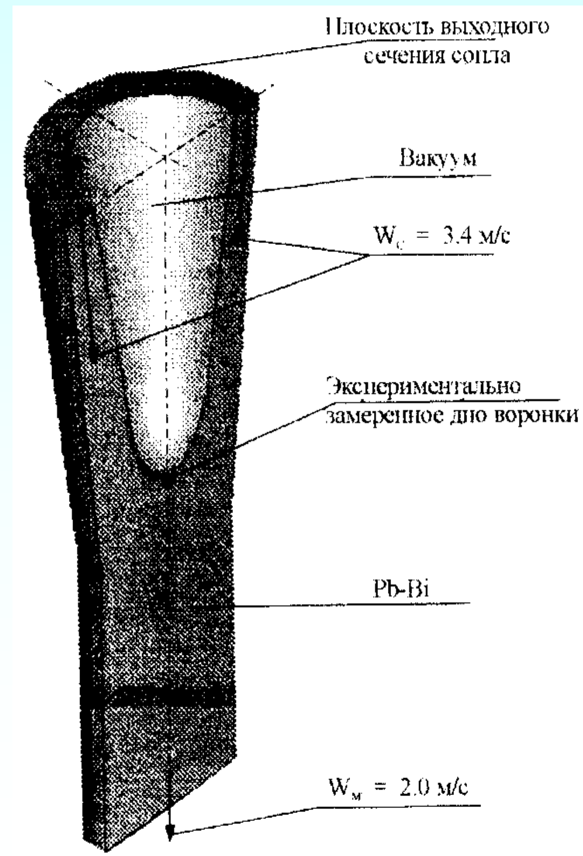
- **The diaphragm is the most vulnerable target component, both from thermal and radiological point of view. Therefore, the work has been started to justify a target design without the diaphragm.**

- **IPPE performed experimental research of the hydrodynamics of vertical and horizontal liquid metal-target without the diaphragm.**

• The studies were carried out with water and liquid metal. It has been shown that the suggested design concepts make it possible to obtain stable funnel-shaped liquid flow in a wide range of hydrodynamic parameters.





# LOS-ALAMOS SCIENTISTS AT THE "WINDOWLESS" TARGET TEST FACILITY

# CONCLUSION

- The experience accumulated in the process of NMPP construction and operation, as well as the results of recent theoretical and experimental studies show that **heavy liquid metal coolants will play an essential role in the nuclear technologies of the 21 century, making it possible to increase the nuclear power safety.**