**CHOICE OF A COOLANT FOR THE MODULAR**

**SMALL POWER FAST REACTOR SVBR-100**

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**Abstract**

In recent years, small modular reactors (SMRs) have begun to be developed in many countries around the world. At the last IAEA Technical Meeting on the Benefits and Challenges of Fast Reactors of the SMR Type (Milano, September 2019), several SMR concepts with different coolants were presented. Interest in such reactors is due to a number of their inherent features: shorter construction time, a higher level of safety, a longer campaign without refueling, etc.). The main difficulty to be overcome is the increase in specific capital costs while reducing the capacity of the reactor module. This limits the market niche of such reactors to regions with high fossil fuel costs. The noted difficulty increases with the use of SMR and for heat supply, which requires the placement of such nuclear power plants at a short distance from heat consumers and requires an increase in the safety of nuclear power plants. The safety level of a reactor is largely determined by the potential energy accumulated in the reactor coolant. The release of this energy when normal operating conditions are violated can lead to a large release of radioactivity, the localization of which requires an increase in the number of protective barriers and their effectiveness. This leads to a rise in the cost of nuclear power plants and a decrease in competitiveness. The report analyzes the properties of various coolants and their influence on the internal self-protection of the reactor, its safety and efficiency, their advantages and disadvantages. Therefore, the choice of a coolant is always a compromise solution. Taking into account the results of the analysis performed, the choice of chemically inert heavy liquid metal coolants with a very high boiling point, lead-bismuth and lead eutectics for fast SMRs is reasonable, since these coolants do not have accumulated potential compression energy and chemical energy. The choice of a lead-bismuth coolant for the SVBR-100 reactor was made taking into account its development in the operating conditions of ship reactors, a practical solution to the problem of ensuring radiation safety associated with the formation of polonium, a significantly lower melting point, which simplifies operation, and the possibility of “freezing/defreezing” coolant in the reactor. This makes it possible to implement the SVBR-100 reactor, which is being developed within the framework of a state-private partnership, with minimal risks.

1. INTRODUCTION

In recent years, small modular reactors (SMRs) have begun to be developed in many countries around the world. At the last of the IAEA Technical Meeting on the Benefits and Challenges of Fast Reactors of the SMR Type (Milano, September 2019), several SMR concepts with different coolants were presented. Interest in such reactors is due to a number of their inherent features: shorter construction time, a higher level of safety, a longer campaign without refueling, possibility to manufacture the reactor in factory and the possibility to build many reactors of the same design, which will reduce costs compared to traditional large reactors.

The main difficulty to be overcome is the increase in specific capital costs while reducing the power of the reactor module. This limits the market niche of such reactors to regions with high fossil fuel costs. However, this limitation will be reduced by a tax on greenhouse gas emissions.

The noted difficulty increases with the use of SMR and for heat supply, which requires the placement of such nuclear power plants at a short distance from heat consumers and requires an increase in the safety of nuclear power plants. The safety level of a reactor is largely determined by the potential energy accumulated in the coolant.

2. POSSIBLE COOLANTS FOR PERSPECTIVE FAST REACTORS

The coolant of a reactor facility (RF) determines its engineering design, safety characteristics and economic characteristics. All coolants have their own advantages and disadvantages, therefore the choice of the coolant is always a compromise solution, which also depends on the requirements for the reactor. The disadvantages of certain coolants can be compensated for by various engineering solutions, however, this may affect the technical and economic characteristics of a nuclear power plant in different ways. Not all tried coolants have been tested in practice (organic liquids, carbon dioxide is used in AGR plants UK, mercury has been used in experimental reactors, etc.).

When choosing a FR coolant, it is also necessary to take into account the degree of its mastering and the expected date of the start of industrial implementation of FR. This is due to the fact that the development of a new coolant requires high costs for R&D, creation and long-term testing of a demonstration reactor. (A new coolant means not only a new substance or chemical element, but also a known coolant used in a new range of parameters, for example, supercritical water etc.).

The experience of nuclear power development shows that this period can be 25-30 years. Therefore, it is advisable to create a FR with a new coolant, for which there is no practical experience, only if the projected costs (usually underestimated in calculations) for its development, operation and decommissioning are justified by the expected benefits from its implementation (usually overestimated).

Below considered various coolants used or proposed for use in promising FRs, their advantages and disadvantages.

**2.1. Sodium coolant**

Sodium has found the most widespread use as a coolant due to its extremely high heat transfer properties. This made it possible to obtain a high specific power density of the core, which, with a breeding ratio BR > 1, provided a short plutonium doubling time. It is this quality of sodium that was decisive in choosing it as a reactor coolant. For the sodium coolant, a great experience was gained in operation of FRs, equipment repairs, and liquidation of consequences of accidents that have taken place.

The most successful experience in the operation of sodium FRs was in Russian Federation (BOR-60, BN-600, BN-800). This experience has shown that such reactors can operate reliably and provide the level of safety required today. However, such natural properties of sodium as high chemical activity in contact with water and air have led to the need to introduce an intermediate circuit of non-radioactive sodium, casing of sodium pipelines and other safety measures that have caused a rise in the cost of nuclear power plants (NPP).

**2.2. Sodium-potassium alloy**

Sodium-potassium alloy, which is inferior in heat transfer properties to sodium, attracted attention by its very low melting point (11 °C for eutectic alloy with a sodium content of 22%). This turned out to be important for reactors of space installations and auxiliary systems of FRs with sodium coolant, as there is no need for a heating system.

The sodium-potassium coolant was successfully used in Soviet space reactors of the BUK and TOPAZ series with thermoelectric and thermionic energy conversion and in the US space reactors SNAP-2 and SNAP-10A. However, the very high chemical activity of this coolant upon contact with air and water, which is possible in emergency conditions, limited the area of its application to space nuclear power installations, despite its advantage over sodium ̶ there is no need for a heating system for the primary circuit.

**2.3. Mercury**

Mercury has found application as a coolant for experimental FR in the USA ­ “Clementine” and in the USSR ­ BR-2 due to its chemical inertness and liquid state at room temperature. The technology of the mercury coolant was mastered in the 40s, when experimental fossil power plants with a binary cycle were created, where mercury vapor was used as a working body in the high-temperature part of the Rankine thermodynamic cycle.

However, mercury has not become widespread in power FRs because of its high chemical toxicity, high fast neutron capture cross section, relatively low boiling point (about 340 °C), and high cost.

**2.4. Lead-bismuth eutectic**

The lead-bismuth eutectic (LBE) has been mastered in the conditions of many years of operation of reactors of nuclear submarines (NPS) in Russian Federation. The main advantage of LBE is its chemical inertness and high boiling point, which gives of the reactor the properties of internal self-protection. A total of 8 NPSs and 2 full-scale ground-based prototype stands were built [1]. The total operating experience in all modes was 80 reactor-years.

On the first experimental nuclear submarine K-27 in 1968, a severe accident occurred with the melting of a part of the core [1]. The cause of the accident was related to the full lack of knowledge of the LBE technology. There were no devices for monitoring the oxygen impurity in the LBE, devices for cleaning the LBE from impurities and maintaining its quality during operation. It took about 15 years to solve the problem of LBE technology and ensuring the corrosion resistance of structural materials. After the reactor facilities (RFs) of serial NPSs were equipped with appropriate devices for monitoring and maintaining the quality of the LBE, the RFs were operated reliably and ensured high speed and maneuverability of Project 705 NPSs (“Alpha” class).

In the development of the reactor technology of using LBE (in a broader sense than maintaining the required quality of LBE), very large funds have been invested, all the fundamental problems of its industrial application have been resolved. The disadvantages of LBE include its low heat transfer properties in comparison with sodium, the generation of the alpha-active radionuclide polonium-210, limited explored resources and a small scale of production, as well as a relatively high cost. These issues are discussed in more detail in Section 4.

**2.5. Lead coolant**

Lead coolant (LC), in comparison with LBE, has a significantly lower level of polonium radioactivity (104 times), significantly lower cost, large scale industrial production of lead and its resource base, which does not impose restrictions on the development of future large-scale nuclear power.

At the same time, LC has a significant drawback ¬ high melting point (~ 330 ºС, versus ~ 125 ºС for LBE), which will complicate operation, require remote methods of carrying out repair work. In addition, the operating temperature range is significantly reduced, since the temperature of the LC from the core outlet is limited, as well as for LBE, to a value of no more than (500–550 °C), determined by the corrosion resistance of steels. On the other hand, the coolant temperature at the core inlet for LC should be significantly higher than for LBE to exclude solidification of the LC in transient modes, start-up and cool-down modes. This leads to a decrease in the temperature difference of the LC in the core at the same power and deterioration of the technical and economic indicators.

Another disadvantage of lead is an increase in its volume upon melting by 3.7%, while for LBE the change in volume upon melting is equal to zero [2]. The range of temperature variation during heating from 20° C to the LC melting temperature of 327 °C is much higher than for LBE. These factors must be taken into account when working out the mode of “defreezing” of the LC, bearing in mind that shrinkage cavities formed during the solidification of lead will form in some places of the primary circuit, and an increase in volume during melting will occur in other parts of the circuit.

**2.6. Gaseous coolants**

There is no relevant experience with regard to the use of gaseous coolants in fast reactors. It can be expected that solving the problem of nuclear reactor safety in an accident with a primary circuit depressurization (LOCA) will require very great efforts due to the significantly higher specific power density of reactor core, when the heat decay removal must be provided by the weak natural convection of atmospheric air without exceeding the permissible fuel temperature. Thus, the problem of ensuring safety in accidents such as LOCA will require very great effort. This can make such a reactor economically ineffective. The high pressure of the gas coolant in the primary circuit deprives such a reactor of its self-protection properties.

**2.7. Molten salts**

Molten salts have been used in US experimental thermal neutron reactors (MSR and MSRE). Their advantages are good compatibility with structural materials at high temperatures and a high boiling point. However, the high melting point of molten-salt coolants (above 400° C) creates great difficulties in operation. Molten salt coolants containing fuel salts and actinides may be promising in association with the considered problems of nuclear transmutation of long-lived radionuclides.

**2.8. Supercritical water**

Supercritical water has been repeatedly considered in various countries as a possible coolant of FRs. The high slowing down of hydrogen nuclei is compensated by the low density of the coolant at supercritical parameters and a small volume fraction of the coolant in the core (tight lattice of fuel elements), which makes it possible to have a fairly hard neutron spectrum in the reactor.

However, one can see the difficulties in ensuring safety in an LOCA accident with association in ensuring reliability at an ultra-high pressure of the coolant, etc.

3. INFLUENCE OF POTENTIAL ENERGY ACCUMULATED IN A COOLANT ON SAFETY AND ECONOMY

The problem of ensuring the safety of NPPs, sharply aggravated after the Chernobyl accident, came to the fore again after the accident at the Fukushima NPP. As a result, the confidence of the population and politicians, reflecting the opinion of the population, in the safety of nuclear power (NP) in a number of countries has decreased, which has caused a slowdown in its development.

At the same time, a further increase in safety requirements, one of the important quantitative criteria of which is the value of the probability of a severe accident requiring evacuation of the population, for NPPs with conventional reactors can lead to the loss of the competitiveness of NP based on such reactors. To reduce the specific capital costs and the cost of generated electricity, an increase in the unit power of the reactors was required, which, however, causes an increase in the total costs of the construction of NPPs, the construction time, which increases financial risks.

Probabilistic safety analysis (PSA) methods are not convincing for the population experiencing a feeling of radiophobia and lose their meaning when the initiating events of severe accidents are not accidental (equipment failures, personnel errors), but are caused by malicious actions (sabotage, terroristic actions), when all safety systems be in standby mode can be deliberately disabled and transport apertures in the protective shell open. Such NPPs in the hands of terrorists can become an instrument of political blackmail, which was the reason for considering this problem in the IAEA [3].

The consequences of the accidents that took place, which generated a wave of radiophobia, have a common cause. They are the result of the release of different types of potential energy contained in various materials and, first of all, in the coolant of the RF [4]: the compression energy of the water coolant and the chemical energy of the interaction of water steam and zirconium. For comparison, in water with operating parameters, this potential energy is ~ 20 GJ/m3, while in LBE and LC it is equal to zero. Therefore, improving the safety of NPP based on RF with a large potential energy accumulated in the coolant requires an increase in the number of safety systems and defense in depth barriers, which reduce the likelihood of severe accidents (but do not exclude deterministically their causes) and the severity of their consequences. This causes a rise in the cost of NPPs.

4. REQUIREMENT TO REACTOR FACILITY SVBR-100 AND CHOICE OF LBE

SVBR-100 is a modular fast reactor of small power 100 MW (e), designed primarily for electricity and heat supply to small towns and industries, to replace the currently used coal-fired fossil power plants (FPPs), which generate the bulk of electricity and are environmental pollutants, emitting billions of tons of carbon into the atmosphere. For this reason, in order to avoid large losses during heat transfer, it should be located at a relatively short distance from heat consumers. The SVBR-100 reactor can also find wide application in developing countries that do not have powerful power systems. Therefore, the main requirement for the reactor is a high level of internal self-protection, which ensures the elimination of the causes of severe accidents requiring the evacuation of the population.

The possibility and expediency of using LBE in the SVBR-100 reactor is due to the following reasons.

The high boiling point of the coolant increases the reliability of heat removal from the core due to the absence of a heat transfer crisis and, in combination with the provided guard vessel of the reactor, excludes LOCA accidents due to the boiling off of the coolant in the event of a leak in the primary circuit, which increases safety. The high boiling point of LBE allows for a higher (in comparison with VVER) coolant temperature at the reactor outlet, a significant increase in the temperature head in the steam generator (SG) and ensure a higher compactness of the reactor facility.

Low pressure in the primary circuit reduces the risk of a loss of its tightness and makes it possible to reduce the thickness of the walls of the reactor vessel and to reduce the restrictions on the rate of temperature change under the conditions of thermo-cyclic strength.

Lead-bismuth coolant weakly interacts with water and air. The processes associated with the loss of tightness of the primary circuit and with inter-circuit leaks of the SG occur without the release of hydrogen and any exothermic reactions. It eliminates the need (as shown by the experience of operation of the RF with LBE [1]) of the fast shutdown of the RF in the event of an inter-circuit leakage in the SG. The core and RF contain no materials that release hydrogen as a result of thermal and radiation effects and chemical reactions with the coolant. All this excludes the possibility of chemical explosions and fires for internal reasons. LBE interacts very weakly with uranium oxide and retains a number of radionuclides that may appear when the fuel element cladding is non-hermetic.

The low coefficient of volumetric expansion of LBE allows to drastically decreasing the size of the volume compensator. But, at the same time, it is sufficient for the natural circulation (NC) of LBE in the primary circuit, providing emergency cooling of the reactor.

The low melting point of the LBE (~ 123.5 °C), close to the melting point of sodium (~ 98 °C), makes it possible to repair the primary circuit equipment and unloading fuel without draining the LBE while maintaining it in a liquid state at a temperature of 160 ... 180 °C due to the operation of the heating system or heat decay release.

The absence of a change in the volume of the LBE during melting/solidification makes it possible to “freeze/defreeze” the LBE in the reactor without deformation and damage to the primary circuit equipment.

In the course of mastering this technology for reactors of nuclear submarines (NPS), a number of scientific and technical problems were solved, which makes it possible to confidently develop the SVBR-100 reactor facility project. These problems include the following.

**4.1. Lead-bismuth coolant technology [5]**

Among the main problems that were solved in the course of the development and operation of RFs of this type, it is necessary to highlight the problem of LBE technology. I.e., a complex of systems and devices that ensure control and maintenance of the required quality of LBE during long-term operation, both under normal conditions of a sealed circuit and in case of SG leak, partial depressurization of the circuit during repairs and reactor core reloading. The functioning of such a 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 on the first experimental NPS of project 645, 1968 [1]. The corresponding methods and devices were developed even later, when the construction of the planned series of nuclear submarines of projects 705 and 705K was completed. Therefore, it was not possible to place the necessary devices as standard ones as part of the RF. Some of the devices were assembled in a shore installation that required connection to a RF once a year.

It should be noted that when developing the SVBR-100 RF design for civil NP, this experience was fully taken into account. All devices for monitoring and maintaining the quality of the coolant (it is necessary to control only one parameter – the content of oxygen dissolved in the LBE) are located in the RF as standard, operate automatically and do not require any special shore infrastructure.

To solve these problems, the following have been developed: devices that ensure the chemical regeneration of lead oxide (a dispersant of the argon-hydrogen mixture), dosing devices (an oxygen mass-exchanger) for maintaining the required concentration of the corrosion inhibitor – dissolved oxygen in the LBE, the corresponding sensors that allow you to control the quality of the LBE and cover inert gas, special filters for cleaning the LBE from insoluble impurities.

Corrosion resistance of materials is ensured by appropriate alloying of steels, preliminary deposition of protective oxide coatings on them, and maintenance of the required concentration of dissolved oxygen in the LBE.

The results of work on cleaning the circuit from slags and ensuring the corrosion resistance of steel are shown in Fig. 1 and 2, respectively.

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| --- | --- | --- | --- |
|  |  | 1459 (последний) |  |
| FIG. 1. Hydrogen cleaning from lead oxide, left before cleaning, right after cleaning | | FIG. 2. Corrosion resistance steel EP-823 after 50000 hours testing in LBE by 600 °C | |

### 4.2. Ensuring radiation safety during work on the equipment with surfaces contamination with polonium-210 [6]

A specific feature of LBE is the formation of an alpha-active radionuclide polonium-210 with a half-life of ~ 138 days when bismuth is irradiated with neutrons.

The radiological hazard of the coolant manifests itself when the LBE or gas in contact with it enters the serviced premises, which took place during accidents and repairs of the RF of nuclear submarines and ground prototype stands during the period of their development.

As the experience of RF operation at nuclear submarines has shown, the release of polonium aerosols and air radioactivity in accordance with the laws of thermodynamics sharply decrease after a decrease in temperature and solidification of the spilled alloy. The fast solidification of spilled LBE limits the area of radioactive contamination and allows the spilled LBE to be removed in the form of solid radioactive waste.

A low concentration of polonium in LBE (at the level of 10-6 at.) and the formation of a thermodynamically stable chemical compound of polonium with lead cause a low concentration of polonium-210 in air during emergency depressurization of the primary circuit.

To carry out repair work on “dirty” equipment, work to remove the leaked coolant (up to 20 tons of coolant leaked from the primary circuit of reactor plant 27/VT), measures were developed for individual and collective protection of personnel (respirators, protective clothing, ventilation organization). In addition, methods of decontamination of equipment and fixation of activity on surfaces, methods of carrying out repair work were worked out, which reduce the risk of dangerous amounts of polonium-210 entering the human body and on the skin.

All personnel involved in the work were subjected to periodic medical examinations and, on the basis of numerous radiometric analyzes of biological samples of personnel (both military and civilian), 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 individual and collective protective equipment used, the correct choice of technology and the organization of repair work. This was also facilitated by the relatively rapid elimination 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 LBE, which accordingly reduces its volatility in comparison with pure polonium.

In one of the works published in the USA [7], the data of a retrospective analysis of mortality among a large group of workers employed in jobs with the allocated Po-210 in 1944-1972 at the Mound Facility and controlled by internal irradiation Po-210 are presented. The authors analyzed the medical protocols of radiometric analyzes (over 160,000 bioassays) of a group of white men in the amount of 4,402 people (104,326 people-years) who worked during this period with Po-210, and compared the observation results with official data on the causes of death of 987 people from this group for the period from the beginning of work to January 1984.

They also compared the mortality statistics of this group with similar data from two control groups of individuals (average for the United States and for the state of Ohio) and concluded that there was no relationship between the internal doses received from incorporated polonium up to 1 Sv (100 rem) and the mortality rate for reasons of malignant tumors. Almost all trends characterizing mortality from various cancers in the studied group of workers were negative, i.e. mortality was even slightly lower than in the two control groups.

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

### 4.3. “Freezing/defreezing” LBE in the reactor facility [8]

An important practical problem was the substantiation of the possibility of multiple “freezing/defreezing” of the reactor facility with LBE, which could be required during long-term staying of the NPS at the Navy base. The absence of LBE shrinkage during solidification and a sufficiently high plasticity at low strength in the solid state make it possible to exclude damage to the RF during the transition of the LBE from the liquid to the solid state and upon its further cooling to the ambient temperature and back. For safe “defreezing” of LBE, OKB "GIDROPRESS" a special temperature-time regime of heating was worked out, tested on large-scale models and on the starboard RF of the Project 645 nuclear submarine after its long stay in the “frozen” state.

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

**4.4. Ensuring high reliability of steam generators [1]**

The first modifications of the LBE reactor facility SGs, as well as the SGs RF with pressurized water reactors for nuclear submarines, did not differ in high reliability. However, lead-bismuth boats with leaking SGs 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 of SGs was associated with the choice of the material of the SG tube system, which changed with the accumulation of operation experience. The technology of reliable tube embedding into tube sheets and the design of the tube spacing unit in the bundle were also developed.

The problem of tube spacing was identified during testing of the MP-7 SG as part of stand 27/VT-5 (second campaign). Soon after the start of operation, regular leaks of steam generator tubes, made of pearlitic steel, resistant to corrosion both in LBE and in a water, began to leak, when all requirements of the water-chemical regime are met. Cutting out the damaged tubes showed that, at the points of contact with the spacer plates, the outer surface of the tubes, as a result of vibration wear, acquired a hexagonal shape with a corresponding local decrease in the wall thickness. This led to rupture of the tubes by steam pressure due to loss of strength.

Therefore, the development of a modernized SG design with rigid spacing of the tube bundle was carried out. This design (MP-7M and MP-8M, for OK-550 and BM-40/A, respectively) was developed by OKB “GIDROPRESS”. Tests at the OKBM full-scale stand have confirmed the extremely high reliability of the new spacing unit.

All these activities led to the fact that, if at stand 27/VT and RFs of nuclear submarines of project 645, SG leaks were the rule, then at serial RFs OK-550 and BM-40/A they became an extremely rare exception. This experience was fully taken into account when developing the SG for the SVBR-100 RF.

**4.5. Resource base, production scale and cost of bismuth**

The reference data available until recently on the explored resources of bismuth did not allow counting on the use of LBE in large-scale nuclear power. However, relatively recently, specialized enterprises of Rosatom ­ JSC “Atomredmetzoloto”\_ and “VNIPI promtechnologii” ­ carried out feasibility studies of the possibility of organizing large-scale production of bismuth in Russian Federation and assessment of bismuth resources in the countries of former USSR. Their results showed that in Russia only on the basis of the explored deposits of bismuth in the Chita region can its cost-effective production be ensured in volumes sufficient to commission about 50 GW (e) of NPPs with FRs using LBE, at a rate of 1 GW (e) per year [9]. In addition, there are large bismuth deposits in the North Caucasus. The fields of Kazakhstan are capable of providing input of ~ 250 GW (e). Japanese researchers have estimated [10] that the available world resources of bismuth amount to about 5 million tons (without price determination).

It should also be noted that in accordance with the general geological and economic regularity, the amount of mineral resources increases in proportion to the square of the price at which the consumer is willing to buy resources.

At the current world prices for bismuth, its contribution to the capital cost for the construction of a NPP based on the SVBR-100 reactor does not exceed one percent. Therefore, the technical and economic indicators of NPPs will worsen insignificantly and with an increase in the price of bismuth.

The price of LBE can be significantly reduced if lead and bismuth are used for its manufacture, which have not been previously purified from impurities of bismuth and lead, respectively, as was done earlier. These are related chemical elements that are difficult to separate from each other.

In the future, with the depletion of cheap bismuth resources, a transition to a lead-bismuth alloy of a non-eutectic composition with a reduced bismuth content, but with an increased melting point is possible. For example, with a decrease in the bismuth content in the alloy to 10% (5.5 times), the melting temperature increases from 123.5 ○С to 250 ○С, which is significantly lower than the melting point of pure lead (~ 327 ○С) and should not yet create great difficulties in the operation of the RF. In addition, after the end of the service life of the RF, the possibility of reuse of LBE in other RFs after appropriate refining is being considered.

5. CONCLUSION

5.1. The use of lead-bismuth coolant in the SVBR-100 reactor is primarily due to its technological mastering under the operating conditions of nuclear submarine reactors. Although this experience is not fully representative for a modular civilian fast reactor, it allows, with minimal risk, to construct an experimental industrial power unit based on the SVBR-100 RF.

5.2. Such natural properties of LBE as a very high boiling point and chemical inertness in contact with water and air give the reactor the quality of internal self-protection against a number of severe accidents that require evacuation of the population for traditional reactors. This allows them to be placed at a relatively short distance from cities and also used for heat supply.

5.3. The aforementioned qualities of internal self-protection reduce the number of safety systems and create prerequisites for the creation of small and medium-sized NPPs not only with a higher level of safety, but also more competitive in a market economy.

**REFERENCES**

[1] *G. I. TOSHINSKY, V. S. Stepanov, L. B. Nikitin, et al.*, “The Analysis of Operating Experience of Reactor Installations Using Lead-Bismuth Coolant and Accidents Happened”, Book by Georgii Toshinskii, “Lead-Bismuth Cooled Fast Reactors”. Collection of Selected Articles and Papers, pp. 42-54, LAMBERT Academic Publishing, 2016.

[2] Handbook on Lead-Bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies*,* 2015 Edition, OECD-NEA.

[3] IAEA-TECDOC-1487. “Advanced nuclear plant design options to cope with external events”. IAEA, February 2006.

[4] *G.I. Toshinsky, O.G. Komlev, I.V. Tormyshev, V.V. Petrochenko. “Effect of Potential Energy Stored in Reactor Facility Coolant on NPP Safety and Economic Parameters”.* World Journal of Nuclear Science and Technology, 2013, Vol. 3, No. 2, 59-64. ([www.scirp.org/journal/wjnst](http://www.scirp.org/journal/wjnst)).

[5] *B.F. Gromov, Yu.I. Orlov, P.N. Martynov, V.A. Gulevsky.* “A Problem of Heavy Metal Coolant (Lead-Bismuth, Lead”,Proceedings of 1st International Conference on Heavy-Liquid Metal Coolants in Nuclear Technologies (HLMC-98), Obninsk, Russia, 1999, Vol. 1, pp. 192‑106.

[6] *D.V. Pankratov, E.I. Yefimov, G.I. Toshinsky, L.D. Ryabaya.* “Analysis of Polonium Danger in Nuclear Power Installations with Lead-Bismuth Coolant”.Proceedings of ICAPP’05, Seoul, KOREA, May 15-19, 2005, Paper No. 5497 (CD-ROM), see also in the book *Georgii Toshinskii*, Lead-Bismuth Cooled Fast Reactors (collection of selected articles and papers), LAMBERT Academic Publishing, 2017.

[7] *Laurie D. Wiggs, Carol A. Cox-De Vore and George L. Voelz.*“Mortality among a Cohort of Workers Monitored for Po‑210 Exposure: 1944-1972 y.y. Epidemiology Section Occupational Medicine Group”, Los‑Alamos National Laboratory, Health physics, Vol. 61, No 1 (1991).

[8] *E.H. Pylchenkov.*“The Issue of Freezing-Defreezing Lead-Bismuth Liquid Metal Coolant in Reactor Installations’ Circuits”,Proceedings of 1st International Conference on Heavy-Liquid Metal Coolants in Nuclear Technologies (HLMC-98), Obninsk, Russia, 1999, Vol. 1, pp. 110‑119.

[9] *G.I. Toshinsky, P.N. Martynov,*“Large-Scale Use of Bismuth in Future Nuclear Power”, Chapter 3 of the book “Bismuth: Characteristics, Production and Applications”, pp. 95-122, New York, Nova Science Publishers, 2012.

[10] *Masakazu Ichimiya,* “A Conceptual Design Study on Various Types of HLMC Fast Reactor Plant”.Lead-Bismuth Technology International Meeting. December 12-14, 2000, OEC/JNC/Japan.