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Research Article

Heavy Liquid Metal Coolants in Nuclear Power

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Abstract

After the severe accident happened at NPP Fukushima 1, the problem of increasing population radiophobia arose again. And that is hampering the process of development of nuclear power, which will play a great role in future and eliminate the release of carbon. One of the ways to rehabilitate the population confidence to the nuclear power is construction of reactors with high level of inherent self-protection and passive safety such as fast reactors with heavy liquid metal coolants. In the closed nuclear fuel cycle those reactors will operate in a mode of fuel self-providing without consumption of natural uranium. In those reactors there is no compression potential energy accumulated in coolant and chemical energy, which in case of the certain unlikely combination of initial events are able to cause radioactivity release requiring population evacuation. Such type reactors can be used both for construction of NPPs with large unit capacity power-units operating in a mode of base load, and for construction of nuclear power plants with small power modular reactors. Those nuclear power plants could be used for generation of electricity and heat, could be located near cities and replace coal electric plants. Due to absence of the large number of safety systems required in traditional type reactors and caused by natural properties of used coolants, the NPPs with such reactors can be more competitive. However, there must be the certain stage of their mastering.

Keywords

Lead; Lead-bismuth; Fast Reactor; Thermal Reactor; Safety; Inherent Self-protection,; Potential Energy; Radioactivity Release; Radiophobia

Abbreviations:

BR - Breeding Ratio; EPR - European Pressurized Water Reactor; FR - Fast Reactor; FPP - Fossil Power Plant; HLMC - Heavy Liquid Metal Coolant; IAEA - IAEA International Project; LBE - Lead-Bismuth Eutectic; LC - Lead Coolant; LCOE - Levelized Cost of Energy; LOCA - Loss of Cool Accident; MA - Minor Actinides; MOX - Mixed Oxide Fuel; NFC - Nuclear Fuel Cycle; NP - Nuclear Power; NPP - Nuclear Power Plant; NPT - Nuclear Power Technology; NS - Nuclear Submarine; PSA - Probabilistic Safety Analysis; PWR - Pressurized Water Reactor; RAW - Radioactive Waste; RES - Renewable Energy Resources; RF - Reactor Facility; RMB - Reactor Monoblock; SFR - Sodium Fast Reactor; SMR - Small and Medium Modular Reactor; SNF - Spent Nuclear Fuel; SVBR - Lead-Bismuth Cooled Fast Reactor; TR - Thermal Reactor; VVER - Water Cooled water Moderated Reactor

Introduction

Water cooled reactors of the PWR (VVER) type, which are the basis of nuclear power (NP) and which way of evolutionary development is long, are reliable in operation and meet the current safety requirements. While operating in an open nuclear fuel cycle (NFC), their competitiveness in costs of electricity will be retained for long as compared with that of coal generating. That is conditioned by low existing costs of natural uranium and absence of their tendency to grow in the nearest and extended-range future, as well as low contribution of the costs of fresh fuel and storage of spent nuclear fuel (SNF) in the cost of produced electricity. Along with that, the existing PWR (VVER) technology has actually reached the upper point of its evolutionary development, and in the future, it can't provide competitiveness of that technology at the world market.

The further progress in nuclear power technologies (NPT) can be only achieved under considerable increase of the temperature level in the primary circuit coolant and generated steam parameters, and, therefore, heightening of the thermodynamic cycle efficiency. As applied to VVER (PWR) type reactors, that can be achieved by use of the water coolant with supercritical parameters (supercritical water-cooled reactor (SCWR)) [1]. However, at that point the conflict between increasing safety requirements and economics requirements is not eliminated. The highlighted conflict that is peculiar to reactor facilities (RF), which use coolants with large amounts of accumulated potential energy (compression energy, chemical energy), is shown in the following: rise in safety requirements due to noticeable increase of NPP power units is inevitably resulting in growth of the number of safety systems and their power capacity, increase of the number of defense barriers. Thus, the capital and operating costs are growing and the NPP competitiveness is lowering. For comparison, under operating parameters in water coolant and heavy liquid metal coolants (HLMC) the values of accumulated potential energy (compression and chemical energy) are twenty and zero GJ/m^3 correspondingly [2].

Along with this the problem of NPP safety assurance that sharpened after happening of the Chernobyl disaster has become strongly acute after the accident occurred at NPP Fukushima 1. As a result, in certain countries it caused decrease of the confidence of the population and politicians, who are voicing the population opinion, to the NP safety. Thus, it caused slowing down of the paces of NP development or phase out in several countries.

Naoto Kan who was a prime minister of Japan when the accident happened at Fukushima said: "I think the nuclear power is the most dangerous form of energy extraction. Moreover, the risks are extremely high to continue to use that technology in the whole." And, further: "The statement of nuclear lobby that the nuclear power is more profitable than use of oil or gas is completely false. Many experts agree with that. With due account of expenditures required to compensate damage caused by accidents or costs of radioactive waste disposal, that energy is much more expensive than hydrocarbons…" [3]. It is not difficult to understand the disappointment of the ex-prime minister of Japan, but it is not true for the projects of the present NPPs, and, moreover, to the nuclear technologies based on fast reactors (FR) with HLMCs. We should keep in mind that three severest accidents, namely: Three Mile Island Unit 2 accident, Chernobyl disaster at Unit 4 and accident at NPP Fukushima 1, occurred at reactors with water coolant.

At the same time, further increase of safety requirements (decrease of the probability of severe accident requiring population evacuation that is one of the vital quantity criteria for NPP safety) can result in loss of competitiveness of NP based on water cooled reactors. For the purpose to reduce the specific capital costs and cost of produced electricity, it is required to increase a unit capacity of reactors, which, in its turn, is leading to growth of total costs of NPP construction and growth of construction terms. Thus, the financial risks are growing. An example is experience of construction of power-units EPR-1650 in Finland (Olkiluoto NPP) and France (Flamanville NPP) with capacity of 1650 MWe. Their terms of construction have increased almost twice, and the cost has raised two or three times more. So, the profitableness of the project is sharply reduced that, depending on the tariff, can cause unprofitability of that project. Moreover, the number of sites required for constructing of those large power units is limited by capabilities of power transmission grids.

Along with this, the probabilistic safety analysis methods (PSA) are not convincing for the population with radiophobia. Use of PSA methods makes no sense when the initial events of severe accidents aren't caused by chance (such as equipment failures, personnel's errors), but they are the results of ill-intended human's actions (such as sabotage, terrorists' actions). In those cases, all safety systems, which are in a standby mode, can be disabled deliberately, and the transport apertures in the protective shell are opened. Those NPPs can be used by terrorists as an instrument of political blackmail, and for that reason that problem was considered in the IAEA [4]. The PSA methods were and are useful. Often they are the only instruments for quantitative assessment of safety parameters. However, their application in the existing types of RFs cannot deterministically eliminate the possibility of realization of low probable severe accident. And that fact doesn't contribute to lowering of population's radiophobia including those countries, where electricity is in deficit, and which are the potential market for construction of NPPs.

In the same time, in future the NP role will be very important as it makes possible generating of electricity and heat without limitations in fuel resources, releasing of harmful substances into the environment and consumption of oxygen, which are resulting in global changes in the earth climate. Development of the renewable energy sources (RES) demonstrating the noticeable progress in technical and economical parameters can only replace a comparatively low part of energy resources. Moreover, it is only possible to develop the RES if the governmental support covering their still low efficiency is assured.

The Global Agreement on Climate, that was accepted by 196 countries on 12.12.2015 and signed on 22.04.2016 at UN Climate Change Conference held in Paris and purposed to replace the Kyoto Protocol, will come into force in 2021. However, it does not specify the concrete ways of lowering of carbon releases into the atmosphere. It doesn't provide establishment of a mandatory tax on carbon release as well. Moreover, the nuclear option isn't mentioned in the Agreement, and that is conditioned mainly by radiophobia of the population, whose opinion is accounted by politicians. Along with that, the large-scale NP development assures the opportunity of considerable lowering of carbon release into the atmosphere.

Ways of Lowering the Population's Radiophobia

The progressive part of nuclear community is beginning to understand little by little that in the foreseeable future it will be possible to eliminate in principle the severe accidents by use of HLMCs[1].

[1]In the presented paper we aren't considering HLMC properties which make possible their efficient use as liquid-metal targets in the accelerator-driven systems and blankets of thermonuclear reactors.

It is confirmed by a growing number of research and development (R&D) works on HLMC cooled reactors carried in the world. At the First International Conference HLMC-98 the Russian experts presented a great number of reports on HLMC technology including those on operating experience of reactors with lead-bismuth eutectic (LBE) at nuclear submarines (NS) [5]. Twelve foreign participants took part in work of Conference HLMC-98. In 2013 forty seven foreign participants took part in work of the Fourth International Conference HLMC-2013. In 2018 the USA acceded to works on HLMC cooled reactors within the Generation IV International Forum (GIF). The Belgian Nuclear Research Centre (SCK•CEN) organized work of annual Heavy Metal Summer Schools. The Global Symposium on Lead and Lead Alloy Cooled Nuclear Energy Science and Technology (GLANST-2017) was held in Seoul (Republic of Korea) in September 2017. The International Symposium on Lead-Cooled Fast Reactor Technology Development was held in Shenzhen (China) on March 14-16, 2018. On March 9th, 2018 the initiative of building China Industry Innovation Alliance of Lead-based Reactor (CIIALER) was lunched in the Industrial Strategy Symposium of Lead-Based Reactor held in Hefei, Anhui Province, China. The CIIALER includes the representatives from over 100 enterprises. As for publications on HLMC subjects in peer-reviewed journals, in 2018 their number can be compared with those on sodium coolant (www.sciencedirect.com). The conclusion made up in the report of Massachusetts Institute of Technology (MIT) [6] predicated a noticeable possible role of HLMC in the future NP:

Use of HLMC in FRs provides the reactor with crucial properties of inherent self-protection regarding to the severest accidents requiring population evacuation. That is conditioned by HLMC nature properties, namely: high boiling point and chemical inertness while interacting with water and air. In HLMC cooled reactors there is no potential energy accumulated in coolant, which upon the certain initial events can cause destruction of defense barriers and catastrophic radioactivity release.

Use of HLMC is forming the backgrounds for simplification of the RF design due to elimination of the certain safety systems required in the RFs with other coolants. Thus, it is possible to construct NPPs on the basis of FRs with HLMC, which aren't only safer, but cheaper, as compared with NPPs based on traditional type reactors.

Though now there is no currency equivalent for the safety level, its enhancement is providing competitive advantages under the similar technical and economical parameters of different type NPP projects and is lowering the financial risks for the NPP owner in the process of operation. Moreover, deterministic elimination of the necessity of population evacuation in events of severe accidents is assuring the higher level of population confidence that can be crucial upon selection of the NPP project for construction. It is much easier to convince the population in the NPP safety if it is provided by nature laws (e.g. absence of pressure in the reactor, lack of hydrogen release assure that explosion cannot occur and so on), which eliminate the internal reasons for those consequences. It is more clearly understood for the people, who consider the events on the basis of their own experience, but not on the results of probabilistic safety analyses.

First, the necessity for development of reactors with the indicated safety level was specified in paper [8] in 1985. In that paper those class reactors were named "inherently safe reactors".

The more detailed justification of the necessity to develop those reactors and general principles of their construction were given in paper [9] in 1990 after the Chernobyl accident happened. The principles of construction of those reactors were presented in details in paper [10] (1992).

In paper [9] it is highlighted that for the population the possibility of catastrophic consequences of the nuclear accident is much more important than the very low probability of its realization despite the fact that in accordance with the reliably received statistical data, the man-caused risks caused by operation of industrial enterprises and their fuel-energy infrastructure are many orders greater than the corresponding risks from the NP. From the standpoint of the nuclear community and educated part of the population, that perception of the NP is not reasonable. However, that factor should be taken into consideration as an objective one and the high safety level of the NPP should be validated for the population, whose opinion is crucial and final, by "transparent" arguments without use of probabilistic analysis methods, if possible.

[2]The issues on finding the solution to the problem of HLMC steel corrosion are described in details in paper [7].

The Role of FRs with HLMC in the Future Large-Scale NP

The future large-scale NP must be competitive with fossil power generating, must not have any limitations in fuel resources, and, at the same time, must deterministically eliminate the severe accidents requiring population evacuation. At present in the world there are no nuclear technologies, which can meet all the highlighted requirements. However, now ongoing development of such nuclear power technologies (NPT) is carried out in many countries.

Today it is generally accepted that the FRs will be significant in the future large-scale NP. It is conditioned by the fact that we can only obtain the breeding ratio (BR) that is equal or exceeding one in fast neutron reactors. That makes it possible to involve ^{238}U (widespread heavy uranium isotope) instead of ^{235}U (rare light uranium isotope) in electric power generating at the NPP. Due to the highlighted fact, the source of raw fuel for the NP can be extended approximately one hundred times and providing the humanity by energy for many thousand years, without carbon release into the atmosphere and consumption of oxygen. To realize that opportunity, the FRs must operate in the closed NFC with recycling of built up plutonium.

Along with that, despite such unchallengeable advantage over the operating water-cooled thermal reactors (TR), the FRs aren't developed widely. Moreover, in reality the time for their economically expedient implementation in the NP is being constantly postponed. For instance, in the USA, where the fleet of TRs is the largest (about 100 GWe), it isn't planned to implement FRs in the current century due to considerable increase of the cost of natural uranium that can result in loss in competitiveness of the NPPs based on TRs, with fossil power plants (FPP).

The main reason is that the FRs are much more expensive than TRs. That is conditioned by the fact that everywhere the sodium was selected as coolant as possessing the best heat-transfer properties, which allowed providing of intensive heat removal in the core and high rate of excess plutonium buildup. Under the circumstances existed in the last seventies the highlighted requirement to FRs was a determining factor, because at that time the resources of cheap nature uranium were explored in small scales and the pace of electric power development and especially NP development was high. The required doubling time of plutonium (and consequently the time of doubling of the number of NPP power units) was ten years and less.

The lower economical characteristics of tradition FRs are determined by additional expenditures for safety caused by nature properties of sodium, namely: extremely high chemical activity when contacting with water and air that is possible in accidental situations. Those expenditures include an intermediate sodium circuit between the radioactive sodium primary circuit and steam-water circuit, the necessity of casing of sodium pipelines, more complicated technology of SNF management, special measures on fire-prevention safety. In the result, the future large-scale NP is necessarily planned as a dual-component one, namely: in the closed NFC the more expensive sodium fast reactors (SFRs) "are feeding" the cheaper TRs by their excess plutonium.

However, at that point it is necessary to account the fact that it is very difficult to construct TRs using only plutonium (MOX fuel). For instance, in France in the PWR type reactors only one third of the core is loaded with MOX fuel. In the remaining part of the core the uranium dioxide is used that is conditioned by requirements for providing of safety on lowering of the probability of reactivity accidents as the value of $ß_{eff}$ for plutonium is three times less than that for ^{235}U. One plutonium recycle is only allowed. As a result, it is obtained slight diminishing of natural uranium consumption and increasing of the cost of produced energy.

At present in most countries, which are developing the NP, there are no external factors highlighted above. For that reason, now the application of sodium coolant for FRs isn't necessarily. The exception is those countries, where aggressive development of the NP is planned and resources of cheap nature uranium are not large (e.g. India, China). That fact should be taken into account upon coming to a decision on the issue concerning construction of reactor BN-1200 in Russia that will make possible retaining of competence and skilled potential in sodium technology. Moreover, that will make possible keeping of "running order" for the functioning NPT based on FRs operating in the closed NFC, which can be required in events of unforeseeable failures in the process of implementation of FRs with HLMCs.

Use of HLMCs as FR coolants, which heat-transfer properties are much worse as compared with those of sodium, doesn't allow obtaining of short doubling time of plutonium. However, due to the HLMC natural properties such as chemical inertness and very high boiling point, the application of HLMCs is forming the backgrounds for construction of FRs with a very high level of inherent self-protection, which deterministically eliminates the severe accidents requiring the population evacuation. At that point, the FRs aren't burdened with additional expenditures for safety required for both water-cooled TRs and SFRs reactors. Due to that fact, after the presented technology has been demonstrated, it is possible that the one-component structure of the future large-scale NP based on FRs with HLMCs is considered as one of the options. However, it will be possible only after the presented technology will be demonstrated.

Along with that the cost of produced electric energy, determining the level of NPT competitiveness, isn't only depending on the values of specific capital costs of NPP construction, but on those of the corresponding fuel cycle. Under existing low costs of natural uranium and absence of their tendency to grow in the nearest future, as well as low contribution of the costs of uranium fuel manufacturing and SNF storage in the electricity cost, closing of the NFC will result in heightening of electricity cost and lowering of NPT competitiveness.

For that reason, at the initial stage of implementation of HLMC cooled FRs in the NP under their technological readiness and lower values of specific capital costs as compared with those of TRs (for the present it is only an assumption confirmed on paper [11]), it is possible that operation of FRs, which use uranium fuel and operate in an open NFC with postponed reprocessing of SNF, can be economically efficient.

That is expedient for the reasons of nonproliferation especially when construction of such reactors is realized in non-nuclear countries, bearing in mind that uranium enrichment does not exceed 20 %. At that point, it is possible to utilize the SNF of TRs step-by-step as makeup fuel in the closed NFC of FRs when closing of the NFC is becoming economically justified.

Though, at that point, the specific consumption of natural uranium is noticeably growing (by a factor of two – two and a half) as compared with TRs, increasing of natural uranium costs caused by accelerated expiration of its economically available resources will not result in considerable deterioration of economical parameters of TRs, which will be dominating in the NP structure till the end of the current century. That is conditioned by low dependence of economical parameters of TRs on the cost of natural uranium. In certain investigations it has been revealed that TRs will not lose their competitiveness even in an event of strong natural uranium cost increase (see paper [6]).

In conditions of limited opportunities of usage of natural uranium and deficiency in existing resources of extracted plutonium for launching of FRs with HLMC, the necessary pace of growing power capacities of FRs with HLMCs can be provided by including of the corresponding number of fast plutonium breeder-reactors with sodium coolant in the NP structure. In that case at the stage of the growing implemented power capacities the NP structure will become three-component, namely: 1) the cheaper FRs with HLMC operating in the closed NFC in a mode of fuel self-providing, 2) the TRs operating in the open NFC, which use partially the uranium fuel and partially the plutonium one, and the SNF is sent to the closed NFC of FRs, 3) the breeder-reactors with sodium coolant, which operate in the closed NFC and supply the TRs by excess plutonium.

The optimum relationship between the reactor types will be determined by their technical-economical parameters and economical parameters of the corresponding fuel cycles. When a stable level of summarized power capacity of NPPs is obtained, a mode of fuel self-providing with breeding ratio that equals to 1 will be quite sufficient. And that is provided by HLMCs cooled FRs operating in the closed NFC with gradual changeover to a one-component structure of the NP.

There is one more feature of the HLMCs cooled FRs, namely: the harder neutron spectrum caused by weak moderation of neutrons on lead and bismuth nuclei as compared with FRs cooled by other coolants. That is resulting in heightening of the efficiency of nuclear transmutation of minor actinides (MA), which possess the threshold dependence of microscopic fission section on power. As a result, while FRs are operating in the closed NFC, in a certain time the concentration of MA nuclei (neptunium, americium, curium) upon their recycling is reaching saturation as the rate of their loss caused by fission is becoming equal to the rate of their formation. At that point, the specific radioactivity of MA (counting on one GW-year of produced power) will decrease with increasing of cumulative energy-generating [12]. So, it makes easier finding the solution to the problem of MA management at the back-end stage of the NFC as long-lived isotopes of MA define the radiotoxicity of wastes, which must be sent to the final burial.

The harder neutron spectrum is also leading to diminishing of the positive constituent of the void reactivity effect by making it negative for small power FRs with high neutron leakage. And that is important for safety.

In Russia LBE (content: Bi – 56 %, Pb – 44 %) mastered in conditions of operating reactors of nuclear submarines (NS) is considered as HLMC. LBE is used in designing of reactor SVBR-100 oriented to construction of small and medium power modular NPPs. Besides, lead coolant (LC) that has not been mastered yet, but that is used in designed reactor BREST-OD-300 is considered as HLMC and as a stage in construction of commercial power unit FR-1200 with lead coolant.

The melting temperature of LBE is much lower (124 °C) as compared with that of lead (327 °C) that is convenient in operation. For that reason, it was selected as a primary circuit coolant in reactor SVBR-100 despite of its higher polonium radioactivity (by four orders greater).

The measures for providing of radiation safety, which were developed upon mastering of that technology regarding to NSs, were efficient [13]. That is proved by the fact that in an event of accidental coolant leaks, the radiation dose of the military and civilian personnel, who took part in eliminating of consequences, didn't exceed the permitted sanitary level. The more so, it is true for RF SVBR-100 that is designed as a monoblock with a guard vessel that eliminates the opportunity of LBE leaks. Under normal operating conditions, the polonium activity of LBE is not showing its worth, though it is a source of potential radiation hazard, which should be accounted while developing the NPP projects based on LBE cooled RFs and operating of such NPPs.

Bearing in mind that the existing single-component NP based on TRs operating in the open NFC with postponed reprocessing of SNF will be competitive with coal generating for several decades, at present there is no economical expedience to implement a large number of FRs in the NP unless FRs are cheaper than TRs. In paper [11] it is shown that it is most likely expected for FRs with HLMCs, which require a mastering stage, as compared with industrially mastered technology of SFRs. At present for the civilian NP the FRs with HLMC are, in the words of Admiral Rickover, "paper" reactors.

Small and Medium Modular Reactors (SMR) with HLMC

In recent years we observe a sharpening interest in development of small and medium modular NPPs, which include the NPP based on RF SVBR-100. Less amount of capital expenditures and shorter terms of construction are required for NPPs based on RF SVBR-100 that lessens the investment risks and makes more possible the attraction of private investments.

In fact, now there are not any nuclear power sources in that power niche, though FPPs of such power capacity produce the major part of electricity and virtually the whole quantity of heat energy, at this point, being the main pollutants of the environment.

Among fifty or more SMR projects developed in different countries, the evolutionary projects based on traditional water technologies are the major ones. On consideration of the near future commercialization, the most real option is a Russian project of floating NPP based on RF KLT-40C and further development of that project on the basis of advanced RF RITM-200.

Among the SMR projects developed abroad there are some projects with HLMC. These are the following projects with LBE: CLEAR (Chinese People's Republic), PEACER and URANUS (Korea), HYPERION (USA), ENHS (USA), MYRRHA with accelerator (EU); the projects with lead coolant: SSTAR (USA), ALFRED (Ansaldo, Italy), SEALER (Sweden). Recently Westinghouse Electric Company LLC has acceded to development works on HLMC cooled reactors.

The high safety level resulting from natural properties of HLMC (such as extremely high boiling point of about 1700 °C eliminating the necessity of excess pressure, chemical compatibility of fuel with coolant, chemical inertness of HLMC while contacting with water and air that is possible in accidental conditions) eliminates the opportunity of explosions and fires in the reactor, which are followed by high radioactivity release. Thus, it is assuring tolerance to the equipment failures, personnel's errors and malevolent actions that is especially viable when the NPPs are located in countries with a high level of terroristic threats.

High safety of SMRs with HLMC makes possible their location in the centers of power consumption or close to the regions, in which raw and mineral mining is performed. Thus, there is no necessity in construction of expensive extended electric transmission lines. Moreover, the losses caused by transmitting of electricity to the long distances and transport expenditures for long-distance transportations of raw materials are reduced as well.

However, small and medium power NPPs, which should replace the FPPs, must meet the higher safety requirements, as, bearing in mind their function of heat supply, they must be located in close proximity to the cities. In addition to satisfy the high safety requirements and technological readiness level, the major restriction on the way of wide implementation of those NPPs in power engineering is difficulty in obtaining of the required value of LCOE (Levelized Cost of Energy). That index is determined as a ratio of discount expenditures over the whole lifetime including capital costs, fuel and operating costs, SNF management costs, decommissioning costs, etc. to the total amount of produced energy. The indicated index is introduced in International Project INPRO for the purpose to compare the competitiveness of nuclear and alternative energy sources.

The highlighted difficulty is caused by a common law of increasing of the value of specific capital costs in construction of NPPs with lowering of the plant power capacity, as contrasted with FPPs, for which the value of LCOE is mainly determined by fuel costs. At the same time, upon discounting, the capital expenditures made prior to NPP implementation in commercial operation are growing, especially when the terms of construction are increasing and the current annual incomes from sales of power are decreasing.

Just the SMRs with HLMC, which are not burdened with large expenditures on safety providing due to a high level of inherent self-protection, possess the advantages of modularity, are entirely factory manufactured and transported to the NPP site in readiness (therefore, there is reduction in terms of construction), and with account of their serial production, have great opportunities to obtain the required values of LCOE, as compared with other types of RFs.

Conclusion

1) The role of FRs operating in the closed NFC will be determining in the future large-scale NP thus providing the humanity with energy for many thousand years without restrictions on fuel resources, releases of harmful products into the atmosphere and consumption of oxygen in huge amounts, lowering the political risks associated with supply of hydrocarbons.

2) Slowdown of the paces of NP development and extension of economically available resources of natural uranium enable to consider the FRs with HLMC operating in the closed NFC in a mode of self-providing as an option for the future NP. Those FRs cannot provide the short plutonium doubling time that is possible to obtain in the mastered sodium fast breeder reactors. However, due to the natural properties of HLMC, in those FRs it is possible simultaneously to enhance safety and improve technical-economical parameters.

3) In the RFs with HLMC the amount of accumulated potential energy in coolant is minimal that makes possible realization of inherent self-protection and passive safety properties to a maximal extent and elimination of the reasons of severe accidents requiring the population evacuation. Those RFs aren't amplifiers of external impacts, and, therefore, the scale of destructions will be only determined by the energy of external impacts. Those type RFs will possess the robustness properties, which will provide their high resistance not only in events of single failures of the equipment and personnel errors (human factor), but in events of deliberate ill-intentioned actions. Such properties of RFs with HLMC will make it possible to overcome the population radiophobia that has grown again after the accident occurred at NPP

Fukushima 1. And that is very important for establishing of large-scale NP and sustainable development. The chain of safety of large-scale future NP shouldn't have a weak links. As the third Director General of the IAEA Hans Blix said, "If the accident occurs somewhere, it is an accident everywhere."

4) The RFs with HLMC, which require a stage for their mastering when real experience in conditions of the operating NPP is gained, can be used both for construction of power units of large unit power, which cover a base part of load, and for construction of SMRs operating in local or regional power systems and generating heat along with electricity. Such NPPs will make possible replacement of coal FPPs, which are the major pollutants of the environment.

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