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Issues of Safety and Civil Liability Insurance for Nuclear Damage from Small Nuclear Power Plants

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Abstract

Purpose: To study the possibility of achieving assured safety for the environment and public in all modes of operation of small nuclear power plants (SNPP) and providing real civil liability insurance for nuclear risks at reasonable financial costs.

Material and methods: Particular attention on small nuclear power plants is driven by regional development, local communities and productions, which are not covered by centralized transport and energy supply. The peculiar properties and benefits of energy production at SNPP are considered, including: the possibility of locating in remote regions; the short construction period and the modular structure of SNPP; availability of potential to improve safety and reliability; reducing the size of the sanitary protection zone up to the boundaries of the technological site; the reality of liability insurance (full financial responsibility of the operator) for nuclear damage to third parties caused by an accident at SNPP at reasonable financial costs; industrial serial production; ability to move the entire nuclear power plants with small modular reactors in the assembled form, etc.

A comparative analysis of the technical characteristics of the SNPP and a conventional nuclear power plant from a safety perspective is made.

Results: The results of the SNPP safety analysis performed on the basis of the design documentation of the floating nuclear power plant "Akademik Lomonosov" is presented, with particular attention to assessing the consequences of design and beyond design basis accidents, in terms of probabilistic safety analysis and assessment of the maximum possible damage to third parties. The maximum possible damage to third parties from severe accidents is estimated to be about 0.5 billion RUR, which is hundreds of times less than damage from a catastrophic accident at a conventional NPP. Estimated costs for insurance of damage to third parties from an accident at SNPP will not exceed 1 kopeck/kWh. Possible approaches to civil liability insurance for nuclear risks and aspects of legal support are considered.

Conclusions: The results of the analysis allow to conclude that it is possible to provide in the future: the achievement of practically assured safety of the SNPP for the environment and the public in normal operation and possible design and beyond design basis accidents; real civil liability insurance for nuclear risks of SNPP at reasonable financial costs.

Key words: *nuclear power plant, low power, transportable installation, safety, accident, nuclear damage, insurance*

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Introduction

Interest in nuclear power based on small nuclear power plants (SNPPs) is steadily growing up through the work of national and international organizations. The IAEA's INPRO on global nuclear energy sustainability addresses issues on legal and institutional support for international life cycles of SNPPs [1–4].

Particular attention to SNPPs is driven by regional development, local communities and productions, which are not served by transport and energy infrastructure. SNPPs are essential for the Arctic and the Arctic shelf regions, for the remote north-east region of the Russian Federation [4, 5]. The constructed floating nuclear power plant (FNPP) "Academic Lomonosov" was delivered by sea to the Arctic town Pevek in Chukotka in 2019, Fig. 1.

The opportunity and expediency of SNPPs deployment in other regions in Russia are also considered. At the international forums at the IAEA the representatives of a number of countries of Africa and Asia pointed out to the need of their countries specifically for SNPPs, not for large-scale nuclear power plants. In the report [5], the available SNPPs world market is estimated at 23 GW(e) until 2040 with a total cost of about $130 billion for the SNPPs deployment.

In addition to Russia, research and development on the SNPPs subject are carried out in China, USA, France and other countries.

Russia has accumulated vast experience in the implementation of life cycles from design to disposal of low-power shipboard nuclear power plants. In the Russian nuclear powered shipping industry accumulated integral experience amounts to more than 6.5 thousand reactor-years, which is equivalent to half the experience of the world nuclear power industry. This experience is largely reflected today in the project of a floating nuclear power plant based on the FNPP "Academic Lomonosov" [6, 7].

This article is devoted to the development of safety quality in the design line of KLT-40 – RITM reactors and the provision of real civil liability insurance for nuclear risks of SNPPs at reasonable financial costs. In this review, the authors largely rely on the materials of Russian domestic project of the floating nuclear power plants based on the FNPP "Academic Lomonosov" with the KLT-40S reactor and materials on the land-based SNPP with the RITM-200 reactor [4, 8, 9].

Fig. 1. Floating nuclear power plant "Akademik Lomonosov" in the strait between Denmark and Sweden during its transportation from St. Petersburg to Murmansk

Civil liability for nuclear risks includes only liability for nuclear damage to third parties. The damage associated with the loss of equipment and the cost of protective and recovery measures after the accident at the SNPP site is not considered here.

Material and methods

Peculiar properties and benefits of energy production at small nuclear power plants

The peculiar properties and benefits of energy production at SNPPs are noted and analyzed in one or another form and completeness in national and international forums on the small nuclear power development, that is:

- possibility of locating in remote regions,
- short construction period and SNPP modular structure,
- having potential to improve safety and reliability (more efficient operation of passive safety equipment, minimization of the logistic component in the SNPP life cycle, etc.),
- relatively greater simplicity of design,
- suitability for non-electrical applications (heat production, water desalination, etc.) and for replacing aging fossil fuel power plants; SNPP is relatively free of greenhouse gas emissions,
- greater flexibility in choosing a site,
- flexibility to meet growing local energy needs by installing additional modules,
- reducing the size of the sanitary protection zone up to the boundaries of the technological site,
- reduced capital costs of the SNPP construction,
- lightweight financing scheme,
- support for the nuclear nonproliferation regime with the SNPP extensive use in non-nuclear countries, with reactor lids, sealed at the manufacturing factories, without nuclear fuel loading and reloading at the deployment sites,
- reality of liability insurance (full financial responsibility of the operator) for nuclear damage to third parties caused by the accident at SNPP at reasonable financial costs,
- possibility of multimodular deployment at the site,
- industrial serial production,
- ability to transport the entire nuclear power plants with small modular reactors in the assembled form, etc.

Comparative analysis of technical characteristics of SNPP and a conventional nuclear power plant from a safety perspective

When comparing potential damage from SNPP and a large-scale NPP, it may be noted that there are significant differences:

Power. The thermal power of a typical NPP unit is about 3 000 MW, and the thermal power of SNPP is an order of magnitude less. Consequently, the residual heat release will be also correspondingly less after the reactor protection system is activated in the event of an accident at SNPP. It reduces the severity of the problem of heat removal after the emergency shutdown of the reactor.

Fuel enrichment. Reactor units of conventional nuclear power plants require uranium to be enriched within 3–5 % U-235 in their fuel, while SNPP uses fuel with enrichment of 15-20 %. U-235. Accordingly, less amount of isotopes of plutonium and transplutonium actinides accumulate in the nuclear fuel in reactors at SNPP, than in the nuclear fuel in reactors at large-scale nuclear power plants.

Amount of uranium fuel in the reactor cores. In conventional nuclear power plants the reactor core contains more than 100 tons of uranium, while the SNPP reactor core contains about a ton of uranium. That's why it is easier and more reliable to provide the emergency cooling to the SNPP reactors than to the reactors at a large-scale nuclear power plant.

Content of radioactive products in the reactor cores. The total content of radioactive products in SNPP reactor cores is less by 1–2 orders of magnitude than in large-scale NPP reactors, and the radioactive releases in the case of any radiological accident at SNPP will be much less than in the case of the reactor destruction at large-scale plants.

Construction and design solutions for SNPP. In addition to the fundamental differences noted above, there are design features to facilitate emergency at SNPP, as compared with large-scale NPPs:

- small dimensions of the equipment make all the SNPP systems more accessible for a inspection in normal, abnormal and emergency situations,
- fewer coolant material needed to prevent accidents or reduce their consequences;
- low residual heat power compared with residual heat power in large-scale NPP reactors,
- possibility of more efficient use of passive safety features;
- floating SNPPs have an additional protective barrier in the form of leak-tight compartment walls in addition to the usual primary containment barrier,
- relatively low residual heat generation rate in the SNPP reactors makes it possible to provide sufficient cooling water reserves for long-term passive core cooling to prevent the reactor core destruction;
- during a core melt accident a small volume of the molten core and relatively low residual heat release determine relatively low heat flux from the molten core at the bottom of the reactor vessel; it allows to successfully solve the problem of preventing destruction of the reactor vessel and achieving in-vessel retention of the molten core by reactor pit flooding (cooling from outside the vessel) in the emergency conditions.

In-vessel retention of the molten core and its cooling to solidification allow reducing the consequences of beyond design basis accidents.

SNPP decommissioning requires a minimum amount of work on the release of the territory (or water area) for further use or rehabilitation works.

SNPP safety analysis

The following safety analysis is based on the materials of the safety analysis of the design documentation of the FNPP "Academic Lomonosov", paying special attention to the assessment of the consequences of design and beyond design basis accidents [6, 7].

Results of the probabilistic safety analysis

In accordance with the regulatory documents to ensure the safety of nuclear power plants, the probabilistic safety analysis (PSA) should be carried out as part of the preparation of the safety justification report. The overall objectives of the PSA are:

- assessment of the safety level of the power unit;
- supporting the development of recommendations to improve technical solutions and organizational safety measures.

The Russian regulatory document NP-022-17 on safety provisions for nuclear power installations of ships and other vessels [10] provides the following safety guidelines in terms of the PSA:

- the cumulative probability of severe accidents does not exceeded 10^{-5} per reactor year;
- the cumulative probability of large emergency radioactive release does not exceed 10^{-7} per reactor-year;
- for beyond design basis accidents at FNPPs, regardless of their probability, organizational measures should be developed to manage such beyond design basis accidents, including measures to reduce the radiation impact on the personnel and specialized personnel, the public and the environment.

The results of the PSA showed that for the FNPP power unit based on the KLT 40S reactor, the core damage probability is $4{,}5 \cdot 10^{-8}$ per reactor-year for the internal initiating events for full power operating conditions [7]. Undoubtedly, the probability of beyond design basis accidents is even less. These results indicate that the requirements of document NP-022-17 are being fully met.

Assessment of the maximum possible damage to third parties

The assessment was carried out, based mainly on the Technical report on the safety justification of the FNPP "Academician Lomonosov" [6]. Some preliminary damage assessments were made in [11].

Due to SNPP design and operational characteristics and peculiar properties, SNPP can realistically be provided with such a high safety level in any possible emergency situations, including beyond design basis accidents, that

- both in terms of the scale of possible damage from accidents and SNPP structure, SNPP is fundamentally different from modern conventional nuclear power plants;
- physical preservation of at least two last safety barriers is ensured;
- almost complete control over nuclear materials and radioactive waste is achieved;
- possible minor radioactive gas and aerosol emissions through the ventilation system can not lead to exposure doses to individuals from the population above the established safety standards at the most severe beyond design basis accidents.

Below are the results of expert assessment of separate components of possible damage from accidents at SNPPs in Russian conditions, taking into account the above-described peculiar properties of the FNPP. Details about SNPP specific location would allow for more accurate assessment of possible damage.

Public health damage assessment. The SNPP safety system allows even in case of beyond design-basis and especially design-basis accidents to prevent high radiation doses – higher, than the maximum permissible doses.

Therefore, the post-accident management will not require such protection measures as resettlement and strict measures of activity limitations. Nevertheless, it is possible for some part of the population to express concerns about their state of health and submit claims for their health damage compensation. In reality these concerns are of a socio-psychological nature, not associated with low-dose exposure. In these circumstances, some expenses will be required for explanatory work, for additional measures of medical care. The expert assessment of public health damage from a possible beyond design basis accident is about 50–150 million rubles.

Assessment of business property damage and personal property damage. Damage of this type will be determined, primarily, by the sudden disruption of electricity and heat supply to consumers. In addition, for some time it is possible deterioration in local product quality associated with fear of a psychological nature. The expert assessment of this type of damage is: ~ 50–100 million rubles.

Assessment of damage caused by sudden power outage. This damage is assessed at 10–100 million rubles. It depends on local conditions.

Assessment of damage to agriculture and fisheries. This damage depends on the SNPP location. There may be some restrictions of agricultural activities and problems with the sale of produce associated with fear of a psychological nature. Expert assessment is: ~ 20–100 million rubles.

The costs of additional measures for radiation monitoring. Additional radiation monitoring may be useful or even necessary to confirm low levels of radioactive contamination from SNPP accidental releases. Its main goal is to calm the local population and administration. The expert assessment of this cost component is approximately 10–100 million rubles.

Total damage assessment. The summation of all damage assessment components above gives the following value of the maximum total damage assessment 500 million RUR. This is hundreds of times less damage from a catastrophic accident at modern conventional nuclear power plants.

It appears that the above-described measures to ensure safety at a possible accident may influence and reduce the nuclear insurance tariff rate. There may also be an increasing factor – the lack of the experience in SNPP insurance and absence of SNPP analogues in the world.

Civil liability insurance for nuclear damage

Features of nuclear accident damage (a large amount of possible damage that is difficult to predict in advance, a very small probability of an accident, etc.) give rise to their specific problems of civil liability insurance for nuclear damage and allocates civil liability insurance for nuclear damage in a separate type of insurance – nuclear insurance [12, 13].

The very low probability of a severe nuclear accident (less than 10^{-5}/year) creates a fundamental difficulty in developing a scientifically based nuclear insurance system. According to the general safety rules NP-001-15 [14], the probability of a severe beyond design basis accident with the release of a significant amount of radioactive substances and failure of the emergency unit should not exceed 10^{-7}/ year.

With such small probabilities and a small number of insured objects, the mathematical expectation (ME) of damage from an accident per year, equal to the product of the total damage from the accident Z by the time probability density *w* (dimension is [year^{-1}]) ME = $\Sigma_i Z_i \cdot w_i$ (sum of possible severe accidents) cannot be as the basis for calculating the insurance premium due to the very low statistical power over a limited time period.

In such conditions, the insurance system is formed due to the requirements of the legislation, based on coordination of interests of the insurer and the insurant and expert opinions using the available data on the object safety and with the participation of regulatory authorities.

Mandatory liability for nuclear damage of the operator of a nuclear installation can be provided by one of the following options:

1) insurance of possible damage from a nuclear accident in insurance companies;
2) insurance in the mutual insurance company (MIC), formed by the operators of nuclear installations;
3) insurance both in the insurance company and the mutual insurance company.

Features of the liability for the nuclear damage of an operator of a nuclear installation led to the creation of nuclear insurance pooling system – insurance through the association of insurance companies – nuclear insurance pools. Currently, there are 26 national nuclear insurance pools, including the Russian nuclear insurance pool (RNIP) [14].

The expansion of the insurance pool and the conclusion of inter-pool agreements (the creation of a mega-pool) allow, on the one hand, to increase the insurance liability limit, on the other hand, serve as some indirect movement towards increasing the statistical power.

The differences between the 1st and 2nd insurance options are as follows:

- Joint-stock insurance companies are of commercial nature and aimed to make a profit from their activities. The MIC is not a commercial organization. The profit received by the MIC can be used to replenish the insurance fund.
- A member of the MIC is both a policyholder (an individual) and an insurer (collectively). The MIC is formed only from policyholders – members of the company.

Article 7 of the Law of the Russian Federation "On the organization of insurance business in the Russian Federation" and the Federal law "On mutual insurance" provide for the possibility of organizing the MIC in Russia. However, in Russia, the MIC in the field of civil liability insurance for nuclear damage has not currently been created.

The advantages of insurance in the MIC over the stock insurance company are as follows:

a) insurance conditions in the MIC may more adequately reflect the principles of liability of operators for nuclear damage, since the insurance conditions are formulated by the policyholders;
b) the MIC can set insurance premium rate lower than the stock insurance company, based on its own estimates of the insured risk and lower business costs;
c) the MIC may insure risks that are not insurable for stock insurance companies;
d) insurance premiums paid by the policyholder are not lost for the policyholder, but are used to increase the insurance capacity of the MIC.

Currently in the Russian Federation according to the Russian legislation and the Vienna Convention of 1963 ratified in 2005:

1) a nuclear operator is liable for nuclear damage;
2) the minimum liability amount and financial security limit is 12.3 billion rubles (beginning of 2019);
3) the State covers the damage beyond the limit of liability for the nuclear damage.

The premium rate per one unit (a percentage of the operator's liability limit for damages) is established by agreement between the RNIP and Rosenergoatom Concern JSC. Since 2000, when it was set at 0.58 %, its value has been decreased and at the end of 2018 it was on average 0.155 %.

If we proceed from this value, the annual electricity production from the SNPP unit with an electric capacity of about 50 MW(e) with the capacity factor of 90 % and the value of the insured total damage from an accident of 500 million rubles, the cost of the third party insurance against damage caused by an accident at the SNPP will be approximately 0.2 kopecks / kWh.

It should be noted that the damage from a severe accident as a result of the loss of a nuclear reactor and other equipment, the expenses for elimination of consequences of the accident at the SNPP is orders of magnitude greater. It is not considered here.

New design developments, which increase the SNPP safety

New design developments are being carried out for small modular reactors, which provide for additional design solutions, which increase the SNPP safety. For example, the RITM-200 reactor, designed for the universal nuclear-powered icebreaker, to be commissioned in the near future, can be used with additional design changes for both ground-based and floating SNPP.

The following design solutions, implemented in the reactor RITM-200 for the SNPP, should be noted [4, 8, 9]:

- integrated composition of the reactor unit: the core and the steam generator are placed in a single robust reactor vessel;
- compactness of the integral-type reactor unit (weight 1.7 times less, the area of the reactor unit in the containment vessel is 2.6 times less than the same parameters of the rector unit KLT-40S);
- lower pressure drop in the primary circuit due to the use of an integrated composition, which increases the level of natural circulation of the coolant;
- uranium enrichment is below 20 %;
- lower power density in the core;

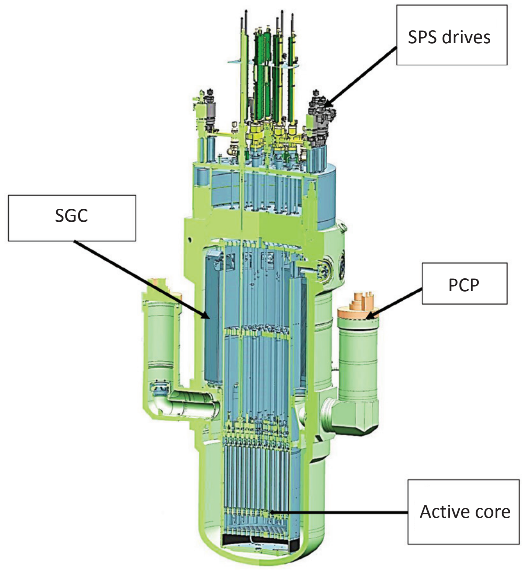

Fig. 2. Reactor unit RITM-200 for SNPP (from the report [9]); PCP: primary centrifugal pump; SGC: steam generator cassette; CPS: control and protection system

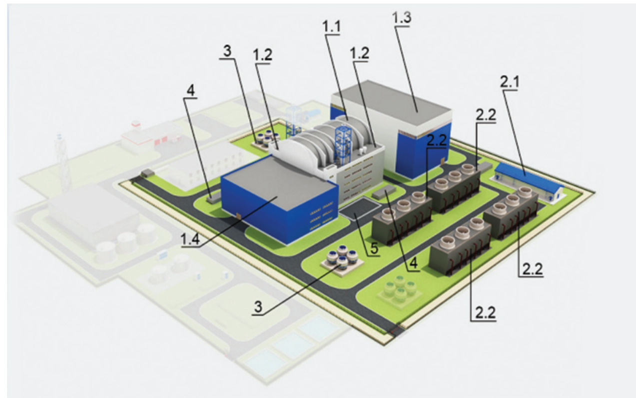

Fig. 3. SNPP on the basis of the reactor unit RITM-200. Site master plan. Plots and complexes (from report [8]).
1 – Main building: 1.1 – Reactor compartment; 1.2 – Engineering system block; 1.3 – Turbine room; 1.4 – Special corps;
2.1 – Pump station of technical water supply; 2.2 – Fan cooling tower; 3 – Responsible Cooling Tower; 4 – Emergency diesel generator; 5 – Temporary storage area for SNF

- 2–3.5 times core lifetime increase compared to the KLT-40S core lifetime;
- high level of safety: the sanitary protection zone does not extend beyond the industrial site;
- probability of severe accidents does not exceed 10-6 per reactor per year;
- high maneuverability of the reactor units (as well as all marine reactor plants);
- ready-to-use spent nuclear fuel (SNF) handling system (based on the SNF handling system for nuclear-powered icebreakers and other vessels);
- significant reduction in the amount of radioactive waste;
- etc.

When developing the project of a floating SNPP with the RITM-200M reactor, it is expected to ensure the absence of SNF storage and fuel overload on board. Fuel will be reloaded only at a specialized plant after completion of the campaign of 8 to 10 years [15].

Summary

The experience of operation of low-power nuclear reactors on nuclear-powered icebreakers, the engineering design of the FNPP “Academician Lomonosov”, including the safety analysis report, the completion of the construction of the FNPP “Academician Lomonosov”, the development of the equipment manufacturing industry for ship-based low-power nuclear reactors, new design developments on SNPP allow to make conclusion on the possibility to ensure in the future:

- achieving practically assured safety of the SNPP for the environment and the public in normal operation and possible design and beyond design basis accidents, meaning the indestructibility of the reactor vessel in a loss of forced cool event and ensuring the functionality of at least two last barriers;
- real civil liability insurance for nuclear risks for SNPP at reasonable financial costs.

New design developments for small modular reactors provide for additional design solutions that increase the SNPP safety.

There are reasons to believe that the existing experience and new additional design developments, aimed at improving the SNPP safety, make it real to achieve assured safety for the environment and the public for nuclear power engineering based on the small modular reactors.

The high level of the SNPP safety for the public and the environment in any emergency situations, and much less possible damage from accidents compared to damage from accidents at conventional nuclear power plants fundamentally change the picture of nuclear insurance.

Within the framework of existing approaches to nuclear insurance, the operator’s full financial responsibility for possible damage to third parties from an accident at an SNPP can really be ensured at reasonable financial costs for nuclear insurance.

Due to obvious financial benefits of nuclear insurance through the MIC for the operator, it is recommended to create the MIC for the SNPP and maintain nuclear insurance for the SNPP through the MIC.

It can be thought that the accumulated experience of designing and operating reactors for the SNPP over time can lead to a change in the structure of nuclear power engineering towards a wider use of the SNPP in the total energy production at nuclear power plants. One of the main factors, affecting such a change, is the high safety quality of the SNPP described above, which excludes the possibility of accidents with catastrophic consequences for the environment and the public.

It is recommended to initiate the development and adoption of amendments to national legislation and international conventions regarding a lower minimum limit of the operator’s liability for nuclear damage in a relationship to SNPP.

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Аспекты обеспечения безопасности и страхования гражданской ответственности за ядерные риски от АЭС малой мощности

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Реферат

Цель: Исследование возможности достижения гарантированной безопасности для окружающей среды и населения во всех режимах работы атомных электростанций малой мощности (АСММ) и обеспечения реального страхования гражданской ответственности за ядерные риски при приемлемых финансовых затратах.

Материал и методы: Растущее внимание к АСММ обусловлено необходимостью развития регионов, локальных социумов и производств, не охваченных централизованным транспортным и энергетическим обеспечением. Рассмотрены особенности и преимущества энергопроизводства на АСММ, включая: возможность размещения в отдаленных регионах; короткий период создания (производства) и модульная структура АСММ; наличие потенциала для повышения безопасности и надежности; уменьшение размеров санитарно-защитной зоны вплоть до границ технологической площадки; реальность страхования (полная финансовая ответственность оператора) ущерба третьим лицам от аварии на АСММ при приемлемых финансовых затратах; индустриальное серийное производство; возможность перемещения атомных станций с малыми модульными реакторами в готовом виде и др. Выполнен сравнительный анализ технических характеристик АСММ и АЭС большой мощности с позиции обеспечения безопасности.

Результаты: Приведены результаты анализа безопасности АСММ, выполненного по материалам проектной документации плавучего энергоблока «Академик Ломоносов», с особым вниманием к оценке последствий проектных и запроектных аварий, в части вероятностного анализа безопасности и оценки максимально возможного ущерба для третьих лиц. Максимально возможный ущерб для третьих лиц от тяжелых аварий оценен равным порядка 0,5 млрд руб., что в сотни раз меньше ущерба от катастрофической аварии на современных крупных АЭС. Оцененные затраты на страхование ущерба третьим лицам от аварии на АСММ не превысят 1 коп/кВт×ч. Рассмотрены возможные подходы к страхованию гражданской ответственности за ядерные риски и аспекты правового обеспечения.

Выводы: Результаты анализа позволяют сделать вывод о возможности обеспечить в будущем достижение практически гарантированной безопасности АСММ для окружающей среды и населения в штатном режиме работы и при возможных проектных и запроектных авариях, а также реальное страхование гражданской ответственности за ядерные риски от АСММ при приемлемых финансовых затратах.

Ключевые слова: *атомная электростанция, малая мощность, транспортабельная установка, безопасность, авария, ядерный ущерб, страхование*

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