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Development Strategy of Nuclear Safety Technology in China

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Abstract: Nuclear safety is a key component of the national security system and is the foundation and lifeline of the nuclear industry. Advanced and reliable nuclear safety technologies are crucial for maintaining and improving intrinsic safety. Therefore, conducting strategic research on nuclear safety technologies is important for enhancing the nuclear industry in China. In this article, we conduct in-depth research on China's nuclear safety technology system using methods including academician interviews, field surveys, conference discussions, and literature reviews. The results show that, guided by the overall national security and nuclear safety concepts, China's nuclear safety technology has made significant progress in recent years, and its nuclear safety performance is good. However, China's nuclear safety technology system faces several bottleneck problems. For example, the nuclear safety standards system needs improvement, the overall planning with respect to nuclear safety software research and development is insufficient, and the precision and advanced nuclear safety equipment still depend on foreign countries. To continuously modernize the nuclear safety governance system and governance capacities and strengthen China's nuclear industry, several suggestions have been proposed. First, the nuclear safety standards system should be further improved. Second, independent high-quality nuclear safety software should be promoted by coordinating scientific research resources to tackle key problems. Third, governments, industries, universities, research, and application need to be coordinated to study and develop high-end nuclear safety equipment.
Keywords: nuclear safety technology; standards system; nuclear safety software; nuclear safety equipment

1 Introduction

Nuclear safety plays an important role in the national security system, which is an important support for other securities, such as territorial security, national defense security, and economic security. Nuclear safety work has high professional and technical characteristics, and the occurrence of serious nuclear accidents historically is related to a defect or lack of nuclear safety technology [1]. Therefore, making continuous innovation in science and technology, improving the nuclear safety technology system, boosting the nuclear safety level in essence, and preventing a nuclear accident are important and meaningful for ensuring national defense security, thereby realizing the healthy and ordered development of the nuclear industry, promoting the construction of an ecological civilization, supporting the high-quality development of the economy and society, and satisfying the modern living needs of residents.

Nuclear safety technology is a scientific theory and technical method to ensure nuclear and radiation safety,

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prevent nuclear accidents, and reduce and relieve the damage caused by nuclear accidents [2]. Increasing attention has been paid to nuclear safety technology after nuclear accidents occurred at Chernobyl, Three Mile Island, and Fukushima. Compared with powerful nuclear countries, China's nuclear safety technology started relatively late, and its foundation is weak. Thus, a number of policy documents have been issued, and relevant work in the nuclear safety technology field has been deployed comprehensively in recent years to strive for advanced international levels as soon as possible. China has made significant progress in nuclear safety law and regulation systems, nuclear safety supervision systems, nuclear safety software, equipment independence, and nuclear safety culture construction, which lay a solid foundation for the globalization of the nuclear power.

To continuously improve the level of China's nuclear safety technology and achieve the long-term goal of becoming a powerful nuclear country, strategic research and top-level design regarding nuclear safety development have been carried out energetically with the support of the "Research on the Development Strategy of China's Nuclear Science and Technology (Phase II)" project of the Chinese Academy of Engineering, including analysis of the nuclear safety technology development of nuclear powerful countries, research on the macro demand of nuclear safety technology for modernized construction in the current era, summary of achieved accomplishments, refinement of existing problems, and proposals for the key direction and research path. Then, suggestions are proposed to provide a reference for China's nuclear safety technology development and management.

2 Developing status of nuclear safety technology abroad

2.1 Nuclear safety standard system improved continuously and regulation operated clearly

Safety standards were formulated in the 1970s by the International Atomic Energy Agency (IAEA) and were massively sorted out in the middle of the 1990s. Subsequently, a high-level nuclear safety standards system was formed by continuous updates and improvements. With the rapid development of the nuclear power industry worldwide, the nuclear safety standards formulated by the IAEA have been an important method to ensure that nuclear power development is safe, efficient, and sustainable. The standards have been adopted by many countries, such as the United States and France, which possess the most nuclear power facilities [3].

Based on the domestic industrial foundation and technical system, an independent nuclear power standards system in line with national conditions was established by the United States and France by consulting the standards system of IAEA. As the nuclear power technologies of the United States and France did not develop simultaneously, their formulating models for nuclear safety standards are different. Independent, complete, and operable nuclear power standards systems were established in the United States and France. With the continuous and intensive development of nuclear safety technology, the relevant nuclear safety standards systems have been updated and improved constantly, which provides a good foundation for the export of nuclear power equipment from the United States and France.

The United States has the advantage of early development in nuclear power technology, and its nuclear standards are the most complete, covering the entire nuclear industry chain. The number of nuclear standards exceeds 1000, and most of them are original [4]. As an import country of nuclear power technology, France has adopted the efficient development path of "introduction–transformation–re-innovation." On the basis of the relevant standards systems of the United States, a special standardization organization was established by France fully considering the influence of domestic laws and industrial foundation, which is responsible for the formulation and unified management of nuclear safety systems. Although the centralized management mode weakens the potential of standards to guide the innovation and development of technology to some extent, it provides great convenience for accelerating the application of industrial systems, reducing the qualification requirements of users reasonably, solidifying the standards contents, and forming a high-quality standards system steadily [4].

2.2 Fundamental research improved and reactor numerical simulation capability enhanced continuously

Nuclear safety analysis software is an important support for the design, construction, and operation of nuclear power plants. Powerful nuclear countries have paid significant attention to the research on nuclear safety analysis software in the process of developing nuclear power technology and have developed nuclear safety analysis software suitable for various scenarios. To verify the effectiveness of nuclear safety analysis software, large-scale integrated performance test platforms have been established (such as the BETHDY test platform of France, ROSA test platform of Japan, and APEX test platform of the University of Oregon in the United States [5]); these play an important role in the application and promotion of relevant software.

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Fundamental research on accident phenomena, mechanisms, and algorithm theory has been significantly enhanced with more intensive studies on nuclear safety analysis software in recent years. By implementing successive projects such as NURESIM, SURISP, and NURESAFE, the European Union has improved the research level of advanced algorithm/modeling and supercomputer platform applications and formed a nuclear safety analysis software system with higher time and space precision with respect to reactor core physics, thermohydraulics, fuel performance, and irradiation performance of materials. In addition, the relevant institutes of the United States have completed the research and development (R&D) of high-precision nuclear safety analysis software with the support of the CASL program and the NEAMS project [6,7]. Benefiting from the accumulation of R&D experience and knowledge achievements in the past decades, the technology state and capacity of the nuclear safety analysis software have tended to be mature, and they play a key role in the design, safe operation, and accident prevention of nuclear power plants.

2.3 Innovation capacity of nuclear safety equipment enhanced continuously and gaining the initiative in the market of advanced-precise-top nuclear safety equipment

Based on the strong industrial base and the advantage of early development in nuclear power technology, the powerful nuclear countries represented by the United States have mastered a series of advanced technologies in R&D, design, production, verification, and maintenance of nuclear safety equipment and formed a complete nuclear safety equipment system by constant accumulation and expansion of independent intellectual property rights and key technologies. Through continuous optimization and improvement, the performance of equipment products has been improved significantly, and the accuracy and reliability have an absolute advantage, which enables these powerful nuclear countries to have the initiative in the market for precision instruments and key equipment. Taking nuclear instruments in a reactor as an example, U.S. and French enterprises have covered various subdivision directions after long-term development. Thermo Fisher has provided more than 650 neutron flux monitors for more than 130 nuclear power reactors in 16 countries or regions, and more than 130 neutron flux monitors for more than 30 research reactors worldwide [8].

3 Achievements of nuclear safety technology in China

3.1 Good performance in nuclear safety and nearly international advanced level in nuclear safety technology

At present, the overall safety situation of China’s nuclear power is stable, with a good safety record. No nuclear accidents of Class 2 or above have occurred in operating nuclear power units. The main operating performance has maintained an advanced level worldwide, and some components of safety indicators have reached the international leading level. The designed performance indicators of newly built nuclear power units satisfy the latest international nuclear safety standards. The quality of the nuclear power units under construction can be controlled. The potential safety hazards associated with research reactors and nuclear fuel cycle facilities have been eliminated, and safety risks have further decreased. The decommission and waste management of nuclear facilities have been continuously promoted. The utilization and management of nuclear technologies has become more standardized. Notable progress has been made in radiation environmental risk management in the mining and smelting of uranium. The ability to resist extreme natural disasters such as floods and earthquakes and the prevention and relief of serious accidents have been further improved, and emergency preparedness and response have been continuously enhanced [9].

3.2 Establishment of a standard nuclear safety laws and regulations system in line with international standards and national conditions

China’s policy and law system has been improved continuously, and nuclear safety has been brought into the overall national security system and written into the *National Security Law of the People’s Republic of China*. The *Nuclear Safety Law of the People’s Republic of China* has been promulgated and implemented, and the legislative deliberation of the *Atomic Energy Law of the People’s Republic of China (Draft for Comments)* has been promoted. A white paper on *Nuclear Safety in China* was published for the first time; it describes the construction route map for the relevant regulations and standards. According to the latest international standards, nuclear safety department regulations have been revised, and the nuclear and radiation safety management system has been improved [10].

3.3 Gaining the expected development of nuclear safety analysis software

The nuclear power design and analysis software package NESTOR, specifically developed for the 3rd-generation advanced nuclear power "HPR1000", has been completed by the Nuclear Power Institute of China with the support of the major nuclear power project "Research on the Independent Technology of Nuclear Power Key Design Software" [11]. COSINE, an integrated software package for reactor core physics, thermohydraulics, and system safety analysis, was developed by the Science and Technology Research Institute Co., Ltd. of the State Power Investment Corporation with the support of the sub-project "Research on Independent Technology of Nuclear Power Key Design Software" of the "Science and Technology Major Project of Large Advanced PWR and HTGR Nuclear Power Plants" [12]. The software package PCM for nuclear design with independent intellectual property rights has been developed by the China General Nuclear Power Corporation, which ensures the design of "HPR1000" reactor cores [13]. The good progress of these specialized software packages have demonstrated our ability to independently research and develop nuclear safety analysis software, providing important assistance for the "going global" of domestic nuclear power equipment.

3.4 Continuous improvement of the nuclear power safety equipment technology and localization rate of nuclear power safety equipment

Based on technology import and independent research, the design and manufacturing technology for most of the key equipment of 2nd/3rd-generation nuclear power islands and conventional islands has been mostly mastered. At present, 2nd-generation improved nuclear power equipment is manufactured domestically. The equipment localization rate of the 3rd-generation advanced nuclear power HPR1000 developed independently is greater than 85%. For example, reactor pressure vessels, steam generators, voltage regulators, and reactor internal components are manufactured in China. On the whole, the localization of key equipment and materials for nuclear power safety has been promoted steadily and are nearly developed independently, except for a few pieces of equipment, parts, and materials.

4 Challenges faced by China's nuclear safety technology

4.1 Construction of nuclear safety standards system needs to be deepened

The nuclear safety standards were sorted out by the Nuclear and Radiation Safety Center of the Ministry of Ecology and Environment in November 2018. Then, a "Table of Nuclear Safety Standards System" was compiled that included eight specialized series, i.e., general, nuclear power plants, research reactor, nuclear fuel cycle facilities, radioactive waste, nuclear material control, civilian nuclear safety equipment, and transport of radioactive materials, which are composed of 111 standards. However, the quantity and integrity of relevant standards are lower than those of the developed nuclear power countries. Nuclear safety standards in key directions, such as modular small reactors, research reactors, nuclear fuel cycle facilities, and nuclear facility decommissions, are still lacking. The standards of decommission plans and decommission characteristic identification plans for nuclear facilities have not yet been established. For example, the standards of decommission design and decommission safety and stock estimation, as well as the rules for overall procedure, safety, and quality for nuclear power plant decommission, are lacking, which does not match the decommission provisions and requirements of the relevant laws, regulations, and constitutions [14].

First, the leading department for the construction of a nuclear safety standards system is not clear, and management present segmentation. This results in a weak nuclear safety technology development system and the coexistence of intersections and missing data. The *Nuclear Safety Law of the People's Republic of China* only stipulates that "the relevant departments of the State Council formulate the nuclear safety standards according to the division of responsibilities," but it does not define the overall and division of responsibilities in detail [15]. In the process of standards formulation, various departments and the development entities of different reactors have their own interest demands, and they hope to dominate the formulation of industry standards with their dominant technology. Competition for the formulation rights of standards increases the difficulty of standards unification.

Second, standards with independent intellectual property rights have not received the required attention, and the relevant basic validation study and experimental data required for the process of standards formulation and improvement are lacking. Taking nuclear island mechanical equipment as an example, some key parameters and indicators lack the corresponding basic experimental data, and the standards formulation still needs to refer to foreign practices [16]. The lack of basic research and basic data has seriously weakened China's participation and

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discourse power in the formulation of international standards. Domestic standards need to be upgraded as foreign standards are upgraded, and a detailed interpretation cannot be accomplished without the support of international and foreign standardization organizations.

4.2 Coordination of R&D of nuclear safety software is insufficient

With the continuous improvement of independent nuclear power software, an independent software platform used for nuclear power export has been preliminarily formed, but it is still specialized for a given reactor. The R&D of independent general software in China is still in its primary stage. Compared with foreign general software, which has been developed for decades and is widely used, there is a large gap in generality, reliability, and stability. The application ability of independent software has not been generally recognized in industry, and the virtuous cycle of use–feedback–improvement has not been established.

First, the top-level design for R&D of nuclear safety analysis software is lacking, and a joint force has not been formed among various participants. In China, software independence has attracted significant attention. Relevant research has been supported by various departments with different types and extents, and relevant nuclear power enterprises and universities have participated. However, the R&D processes are separated, so they lack resource coordination. Duplication, intersection, and omission phenomena exist in R&D. The sharing and compensation mechanism for experimental data, reactor operation data, and the benchmark question database is insufficient, cooperation is insufficient, and a unified sharing platform has not been established at the national level.

Second, the basic research on software algorithms and complicated phenomena is relatively weak. The R&D of nuclear safety analysis software began comparatively late. Although basic research has improved in the past decade, it has been promoted by learning, imitation, digestion, and absorption. There is still a gap between the existing software and the advanced international level because of the lack of exploration of software R&D frontier issues, such as phenomena, mechanisms, analysis models of serious accidents, and well-posedness and accuracy of the two-phase flow algorithm.

Third, the quality control level of nuclear safety analysis software needs to be improved. The software requires strict verification and validation, including analysis, evaluation, review, inspection, assessment, and testing of program products and processes. *Development and Application of Computer Software for Nuclear Power Plant Safety Analysis* issued by the National Nuclear Safety Administration in 2014 has preliminarily established the standards regarding a development and review system for nuclear power software. It should also be noted that China's engineering level for nuclear safety software is not high, and the product quality control system requires a certain amount of time for iteration and perfection. Developers and reviewers also need to accumulate more experience to overcome the shortcomings of weak technical means and awareness of quality control, difficulty in ensuring software quality, and low software validity/reliability/maintainability [17].

4.3 Sophisticated nuclear safety equipment depends on other countries

In response to the "going global" strategy for national nuclear power, nuclear power equipment localization has been continuously promoted. In the promotion process, the localization rate was given a great amount of attention, but the development of some key nuclear safety equipment, core parts, and materials were neglected, which resulted in a number of parts and materials depending on imports. In addition, the quality control of domestic equipment and materials needs to be further improved.

First, a market mechanism that is guided by industrial policies and combines industry, universities, and research institutes is incomplete. The manufacturing process has gradually matured and solidified in the continuous application and improvement process, which ensures that the product is quality-controllable, performance-stable, and constantly improving. Because there is a gap in quality between some domestic key nuclear power equipment and foreign equipment, nuclear power owners tend to choose foreign equipment with mature technology, which leads much domestic equipment to remain in the research stage or initial engineering stage. Domestic equipment cannot be applied from laboratories and factories to practical engineering, so it is difficult to find potential problems in related engineering applications, let alone precise improvement [18]. Taking nuclear instruments used in the reactor as an example, the R&D ability and production process improvement are not sufficient, product batch consistency is not high, and industrialization ability needs to be improved. These problems cause the reliability and consistency of domestic products to be weaker than those of foreign products, which affects the selection of products by nuclear power owners.

Second, investment in basic research, such as new principles, new methods, raw materials, and components, is insufficient. Although the localization level of nuclear safety equipment has increased continuously, the manufacturing technology level of precision and high-reliability equipment of domestic enterprises still lags behind that of foreign countries. Some key parts and materials must be imported in large quantities. Some key technologies (such as R&D, design, manufacturing, testing, and maintenance of various types of nuclear class-1 valves) have not been completely mastered by domestic equipment enterprises, and some key manufacturing processes (such as vanadium wire manufacturing, fabrication of self-powered detectors, and welding of mineral insulated cables and connectors) are still in the exploration stage [8]. Some key components (such as high-performance detectors and photomultiplier tubes used for the production of radiation detection equipment) depend on imports [18]. In addition, many domestic manufacturing enterprises have stayed in the imitation stage, so product performance is not advanced. Taking nickel-based welding rods as an example, the performance of domestic rods is similar to that of foreign countries only in terms of chemical composition and mechanical properties, but the welding operation performance is obviously weaker, with issues such as arc instability, poor slag removal ability, and poor current adaptability.

Third, the construction of a quality culture and nuclear safety culture for nuclear safety equipment is insufficient. The construction of a quality assurance system and nuclear safety culture has not kept pace with the breakthrough of new equipment and technology, and as a result, the implementation of process discipline is not strict enough, low-level errors frequently occur, and the overall quality of equipment is not rigorously controlled. Taking the Sanmen nuclear power plant as an example, many quality problems occurred in the manufacturing process of the AP1000 nuclear island main equipment in phase I, which had detrimental effects on the manufacturing period and cost of the equipment [19].

5 Key directions and development steps of nuclear safety technology in China

5.1 Nuclear safety standards system

By 2025, nuclear safety standards of important areas such as nuclear facility decommission and small reactor management should be improved gradually to form a system, and the quality of standards should be constantly enhanced. An independent, unified, coordinated, and advanced nuclear safety standards system compatible with the development level of nuclear power will be formed.

By 2035, bilateral and multilateral cooperation mechanisms among nuclear power trade countries should be established and continuously promoted. Standardization research and scientific research achievement transformation will be comprehensively launched. The mutual recognition of standards, standards co-construction, and technology exchange and cooperation should be promoted steadily, which can enhance China’s discourse power in the formulation of international nuclear safety standards.

By 2050, the nuclear safety standards system should reach the world-leading level and ensure the safe and sustainable development of nuclear power both in China and abroad.

5.2 Independent software for nuclear safety analysis

By 2025, a national-level laboratory for nuclear safety analysis software should be established based on the major demands of nuclear safety, and research on nuclear safety software R&D strategy and policy should be carried out. Breakthroughs in basic research such as phenomena, mechanisms, and algorithm theories should be achieved by concentrating the advantages of scientific research institutions, universities, and enterprises, which will support the independence of nuclear safety analysis software in key directions. Independent software should be demonstrated and applied in various nuclear power enterprises and research institutions, initially achieving the development of test–feedback–improvement and promoting the globalization of domestic nuclear power.

By 2035, independent nuclear safety analysis software should be realized completely, and the level should meet or partially exceed that of foreign nuclear safety analysis software in key directions. The capability of the experimental verification platform should be continuously improved, and a part of the key platforms should gain international recognition.

By 2050, independent nuclear safety software should be extensively applied and verified in engineering, which should reach the world-leading level and be applied widely in the international market.

5.3 Key nuclear safety equipment

By 2025, the long-term sustainable cooperation mode between domestic nuclear power owners (including

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nuclear facility operation departments) and suppliers should be formed. On the premise of nuclear power safety operations, domestic equipment should gradually replace foreign equipment.

By 2035, nuclear power equipment enterprises should cooperate with nuclear power owners to maintain high-quality development of domestic equipment, and a stable and efficient nuclear power equipment supply chain should be formed. The problems should be found and solved continually by an empirical feedback system, and R&D ability should be accumulated. The market competitiveness of domestic suppliers should be increased, and they should be encouraged to participate in international market competition and cooperation. The cost of nuclear power construction should be reduced significantly, and domestic nuclear power equipment should be recognized by the international market.

By 2050, key nuclear safety equipment, parts, and materials should meet or partially exceed the international leading level. The cost of nuclear power construction should be further reduced, and domestic nuclear power equipment should occupy a large share of the international market.

6 Countermeasures and suggestions

6.1 Improvement of nuclear safety standards system

In view of the current lack of nuclear safety standards in some fields and a lack of independent and unified systems, the following suggestions are provided. The relevant supporting documents of the *Nuclear Safety Law of the People's Republic of China* should be formulated as soon as possible, which can provide the top-level basis for the construction of nuclear safety governance systems. The top-level design of nuclear safety system construction should be given sufficient attention, and the relationship between power and responsibility of the relevant administrative departments should be clarified to outline the division of responsibility. The overall framework system, basic connotation, and development roadmap of nuclear safety technology should be formulated. Basic research on nuclear safety standards should be reinforced. In the process of research and formulation of standards, quantitative indicators should be defined to improve operability.

6.2 Coordinating resources and tackling key problems to enhance the development of independent nuclear safety software with high quality

To solve the problems of imperfect sharing mechanisms, weak basic research, and insufficient verification and confirmation of independent nuclear safety software, there should be unified organization and coordination, systematic and scientific planning demonstration, comprehensive and strict quality assurance standards, scientific and reasonable platform validation, and authoritative and fair confirmation institutions. It is suggested to maintain the unified management of R&D for independent nuclear safety software and coordinate the research sources and factor allocations of the relevant R&D entities to establish a sharing mechanism for the experimental platform and basic data. Basic research on software algorithms, mechanisms, and phenomena should be enhanced, and a solid foundation for the improvement of independent nuclear safety software should be laid. The construction of a quality assurance system for nuclear safety software should be completed, and the demonstration, application, and promotion of independent nuclear safety software should be carried out.

6.3 Paying more attention to the basic research of nuclear power equipment and conducting the quality construction of domestic equipment

In view of the insufficient independence and control of sophisticated equipment, key components, and materials, the following suggestions are provided. Basic research on the processing and manufacturing technology of nuclear-grade equipment, components, and raw materials should be carried out. Based on the institutional advantages, the superiority entities should be arranged to solve the basic, strategic, and bottleneck problems by giving consideration to planning and the market. The problem of equipment independence should be solved precisely and effectively by giving full play to the regulation and leading effects of the market, supplemented by policy guidance and resource support. The quality standard system of nuclear safety equipment should be improved, and the nuclear safety construction of manufacturing enterprises should be enhanced.

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