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Low-temperature nuclear heating reactors: Characteristics and application of licensing law in China

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As one type of small modular nuclear reactor (SMR), the low-temperature nuclear heating reactors (LTNHRs), which have the characteristics of small size, a large power ratio, and good adaptability, can help provide energy in winter as well as reduce greenhouse gas emissions. Despite a growing number of LTNHRs worldwide, a mature legal regulatory system specifically targeting LTNHRs remains undeveloped. Further, few discussions have focused on the prospect of regulating LTHHRs and how national and international frameworks can respond to the new and increasing development of LTNHRs. Given the growing prominence of LTNHRs, this article aims to fill in the research gap by exploring possible regulatory pathways for LTNHRs and whether the existing nuclear regulatory frameworks developed for large reactors could be sufficiently applied to LTNHRs. The article examines and analyzes the prospects and potential challenges for regulating LTHHRs, specifically in the field of licensing. In particular, the article takes the Chinese nuclear legal system as an example to analyze whether the existing legislation and regulations can meet the new requirements for licensing of LTNHRs—given their unique characteristics—in China. Finally, this article proposes suggestions to address the obstacles to regulating LTNHRs, including amending the existing international regulatory framework, improving licensing supervision throughout environmental assessment and public participation, and strengthening international legal cooperation, to ensure the robust and reasonable development of LTNHRs worldwide.

KEYWORDS
LTNHRs, licensing, regulatory framework, China, international cooperation

1 Introduction

1.1 Development of LTNHRs and their characteristics

1.1.1 Promises and limitations of LTNHRs

Small modular nuclear reactors (SMRs) have been receiving an increasing amount of attention from industry, academia, and government because they represent a technological alternative that overcomes problems with other nuclear projects. SMRs differ from traditional large-scale nuclear power plants, namely in terms of two characteristics: being "small" and "modular." (IAEA, 2020) SMRs are a new generation of reactors that are designed to generate electrical power, typically up to 300 MW (IAEA, 2021a). SMR modularity means that SMR components and systems can be shop fabricated and then transported as modules to the project site for installation as demand arises[1]. SMR designs also incorporate emergency planning considerations as part of the design, with enhanced safety guarantees. Limiting an emergency planning zones (EPZ) means that users of the plant's output can be located closer to the plant and significantly reduces emergency planning costs (Kelk et al., 2021). The SMR technology would also offer opportunities to expand the role of nuclear energy as a means of decarbonization (NEA, 2022). All these characteristics provide the basic premise for large-scale production and wide use of SMRs.

As one type of SMRs, low-temperature nuclear heating reactors (LTNHRs) are making progress and are poised to become a commercially viable nuclear product. "LTNHR" refers to a nuclear reactor dedicated to generating heat energy to meet a certain need. Different from other nuclear reactors, maintaining a relatively low temperature during operation is its basic feature (IAEA, 1987). Another basic characteristic of LTNHRs is being able to operate at low temperature for a long time, which addresses the risk of overheating faced by traditional large-scale nuclear power plants[1]. Combined with the basic attributes of SMRs, LTNHRs have the advantages of being inherently secure and being readily scalable. In addition, they offer high reliability, a mature technology, a simple system, stable operations, a small occupied area, low construction cost, and convenient operations and maintenance (Wang, 2018). Their techno-economic features can help to overcome the delivery challenges encountered in recent large nuclear projects and additionally increase the value proposition of nuclear technology, thereby facilitating the provision of flexible and dispatchable low-carbon electricity and heat[1].

LTNHRs, however, also have some shortcomings. Their economic viability is limited because of a limited availability of appropriate sites. Due to the cost of technology development, LTNHR financing is higher than that for traditional heating methods such as coal heating. Transmission *via* high-voltage power lines can reduce energy loss over long distances. Heating must be built close to densely populated areas (Cn energy news, 2021). If the traditional site selection requirements of large-scale nuclear power plants are mandated for LTNHRs as well, this would negatively affect their economic advantage. In addition, the Chernobyl and Fukushima nuclear accidents have eroded the confidence people have in the safety of nuclear energy, and "not in my backyard" resistance to LTNHR facilities may also impede their development.

1.2 Nuclear safety licensing of LTNHRs

A nuclear safety license is a legal document issued by the national regulatory agency to permit nuclear facility operators to engage in specific nuclear safety–related activities (such as site selection, construction, operation, and decommissioning) (IAEA, 2022b). Nuclear safety licensing ensures that the risks to the health and safety of people and the environment from nuclear installations, at all times during their lifecycle, and their activities are properly controlled by the persons or entities responsible for the nuclear facility and operations[1] The licensing process should facilitate efficient validation of safety, which in turn facilitates efficient performance of regulatory activities. The lifecycle of LTNHRs includes siting and site evaluation, design construction, manufacturing, offsite commissioning, transportation, onsite commissioning, operation, onsite decommissioning, offsite decommissioning, and release from regulatory control (IAEA, 2009). Nuclear installation operators therefore need to systematically conduct safety evaluation and verification activities required by regulations and standards at different stages and submit documentation to nuclear safety regulatory authorities for review (IAEA, 2022a). Only after passing review and obtaining the relevant licenses or approval documents can operators conduct activities such as site selection, construction, operation and decommissioning. In China, for example, the National Nuclear Safety Administration supervises and inspects the nuclear safety activities conducted by license holders as part of the approval, supervision, and management of licenses to ensure that license holders are accountable for safety and conduct nuclear activities in accordance with the law.

International regulators have striven to implement licensing processes that are clearly defined and communicated, systematically performed, and transparent and traceable through proper records management. In terms of safety, both the Convention on Nuclear Safety (CNS) and the 2009 Euratom Safety Directive as amended in 2014 apply to "nuclear installations." (IAEA, 1994) The CNS defines a "nuclear installation" as "any land-based civil nuclear power plant under its jurisdiction" [Article 2(i)]. However, when determining whether the CNS applies to LTNHRs, the interpretation of the terms "land-based" and "nuclear power plant" are crucial because the definition of "nuclear installation" only applies to "land-based" nuclear power plants; as such, floating LTNHRs would presumably not be covered.

Access to information, public participation in decision-making, and access to justice are three important pillars of nuclear safety licensing of LTNHRs. In terms of public participation, the Espoo Convention requires parties to complete an environmental impact assessment (EIA), which includes the participation of members of the public from both the party of origin and those of affected parties and the preparation of an EIA (Article 2(2)) for those proposed activities listed in the convention that are "likely to cause significant adverse transboundary impact." (The United Nations Economic Commission for Europe, 2017) The Aarhus Convention also stipulates public participation during licensing. Access to information requires that environmental information be provided upon request and that environmental information be proactively collected and disseminated; this provision applies regardless of the type of activity in question (The United Nations Economic Commission for Europe, 1998). In terms of projects for which public participation is necessary in decision-making, as with the Second Amendment to the Espoo Convention, Appendix I lists "Nuclear power stations and other nuclear reactors." Should all or some LTNHR technologies be covered by this definition, the relevant public must be provided with information about the proposed activity and be allowed to provide comments. If the public's rights under the first and second pillars were violated, the requirement of access to justice would then give them standing to seek redress.

International legal provisions for SMR, in particular for LTNHR, are still in the initial stage worldwide (Popov, 2022). The main reason is that the SMR has not achieved the required profitability metrics and market demand[2]. The IAEA has intensified its work in the development and licensing of SMRs in recent years. It has been working on reviewing the applicability of IAEA Safety Standards to SMRs and has completed the review of over 60 safety standards to guide their application to SMRs (IAEA, 2021b). The Nuclear Harmonization and Standardization Initiative (NHSI) launched by the IAEA, aiming to facilitate the safe deployment of SMRs and other nuclear technologies, has brought together different stakeholders to develop unified regulatory approaches to SMRs (IAEA, 2022a). It will definably help to provide concrete actions for regulators to develop more standardized approaches for construction, commissioning and operation of SMRs, thus to better achieve the green development under the Paris Agreement.

National and international initiatives have also been adopted to promote SMR regulatory frameworks. For example, the US government is supporting SMRs through a reform of the legislative framework for nuclear power. The 2018 Nuclear Energy Innovation and Modernization Act (NEIMA) provides that the US Nuclear Regulatory Commission (NRC) is to adapt the certification process to the specificities of SMR design. In its Advanced Reactor Policy statement, the NRC encourages early interaction between potential applicants and the NRC to provide for early identification of regulatory requirements for advanced reactors. Such early interaction adds stability and predictability to the licensing process by enabling the NRC to develop licensing guidance and to identify and resolve potential policy and technical issues early in the licensing process (NEA, 2021). The NRC has issued a series of regulations regarding issues such as "siting SMRs, security requirements, operator staffing for multi-module facilities, and the defense-in-depth philosophy for advanced reactors" (Energy.Gov, 2012). In 2016, the Canadian Nuclear Safety Commission (CNSC) also launched a new, optional pre-licensing framework to foster engagement with innovative SMR developers. This new licensing framework has led to 10 SMR vendors being currently engaged in the pre-licensing process and one advanced SMR vendor already being engaged in the licensing process to build, own, and operate a first demonstration unit at the Canadian National Laboratories site in Chalk River by 2026 (DIS-16-04 and Small Modular Reactors, 2022). Provinces, including Ontario, New Brunswick, Saskatchewan and Alberta have cooperated to advance SMRs under a Memorandum of Understanding (Government of Ontario, 2022). Promoting a strong nuclear regulatory framework has also been identified as one of five priorities for SMR development and deployment for CNSC. Compared with Chinese licensing system, the regulations of IAEA and other jurisdictions focus more on regulating SMRs in general, rather on licensing LTNHRs particularly.

1.3 Diversified use of nuclear energy and small reactors in China

As a safe, clean, efficient, and large-scale alternative to coal power, nuclear energy is an important element in China's efforts to build a clean energy system. Nuclear is slated to play an important role in optimizing the energy structure, reducing greenhouse gas emissions, and achieving green development. China has also begun to explore the diversified use of nuclear energy, which provides a great opportunity for the development of SMRs, including LTNHRs. Winter heating is of considerable importance in China, with the populations of 17 provinces requiring heating in winter in China; these provinces account for more than 60% of the country's territory and 700 million residents (Zeng et al., 2022). China presently burns hundreds of millions of tons of coal every year to provide centralized heating, causing heavy smog in winter. With the aim of achieving the goal of carbon neutrality, for the Chinese government, it is urgent to adopt SMRs to reduce carbon emission.

In parallel to its national program for large nuclear power plants, China is diversifying its technology portfolio with a number of advanced SMR designs under development. SMR designs are being developed with the objective of providing district heating applications in the north of China. For example, in 2010, China National Nuclear Corporation (CNNC) officially launched the Linglong-1 special scientific research project, which, in April 2016, became the world's first SMR to pass the International Atomic Energy Agency (IAEA) general safety review, setting an important milestone in the development of small reactors worldwide. (Keywords to Understand China, 2021). In July 2019, CNNC announced the launch of the Linglong No. 1 multifunctional modular small reactor demonstration project. (China National Nuclear Corporation, 2019). In addition, at the end of 2019, the first nuclear energy heat supply project built by SPIC Shandong Nuclear Power Company entered operation in Haiyang, Shandong Province. Residents and buildings in the 700,000 m^2 community are now using clean energy, marking the end of their use of coal burning for heating and opening a new era of comprehensive utilization of nuclear energy in China (People.cn, 2019).

In terms of LTNHR development, the Institute of Nuclear Energy Technology of Tsinghua University proposed the development of such reactors in 1981, and from the winter of 1983 to the spring of 1984, China conducted nuclear heating for the first time. Since the 5-MW low-temperature nuclear heating reactor was completed and brought online in November 1989, the NHR200-I type reactor has been popularized and successfully deployed at the end of the 20th century (Hao et al., 2021). The NHR200-II low-temperature heating reactor was successfully developed in 2006, representing how China's development of LTNHRs has gradually moved from experimentation to practice. On 10 July 2019, the first phase of the Haiyang nuclear energy heating project officially started, and on 9 November 2021, residents officially began to obtain nuclear-generated heating (Xinhua News, 2022). In addition, in August 2007, the first phase of the Hongyanhe Nuclear Power Plant, which is located in Wafangdian City of Liaoning Province, started construction. Unit 1 became operational on 6 June 2013, (China General Nuclear Power Group, 2017a) and Unit 6 met the commercial operation conditions on 23 June 2022, making it the third largest nuclear power plant in the world with a total installed capacity of 6.7 million kw in operation. The "Yanlong" (DHR-400) LTNHR developed by China National Nuclear Corporation (CNNC) has also been officially announced in 2019. (China General Nuclear Power Group, 2017b). On 26 September 2022, it was officially announced that the first nuclear energy heating project in Northeast China will be started, meaning that some areas in Northeast China will be able to use nuclear energy for heating in winter 2022, with a planned heating area of 242,400 m^2; as noted, such heating is more efficient than traditional coal-heating with no carbon emissions. (GMW.cn, 2022).

As shown in the above practices, after China's decades of commercial development and experiment verification since the research initiative of LTNHR was proposed in 1981, the technology of LTNHRs is getting more and more mature. Good practices of deployment of SMRs can serve as the basis for establishing the regulatory framework for LTNHRs[1]. However, China is still in the initial stage of commercial operation of LTNHRs. There is still a significant gap of the regional distribution of large-scale LTNHRs in winter (Zeng et al., 2022). In addition, although the Chinese government vigorously promotes clean heating in North China, nuclear energy has not been attached enough importance for development, and relevant policies have not included detailed plannings of deployment. The low public

10.3389/fenrg.2022.1060126

acceptance of nuclear reactors also obstacles the promotion of deployment of LTNHRs.

2 Analysis of LTNHR licensing system in China

There is no outstanding evidence showing that China's LTNHR development practices have promoted China's domestic law in regulating LTNHRs. However, the practical examples that reveal the shortcomings of the existing regulatory system, could improve China's LTNHR licensing system to some extent in the future. China's current laws and regulations regulating LTNHRs have included laws, administrative regulations, departmental regulations, technical documents, and associations and group standards. Although association and group standards, recognized by the state, are adopted voluntarily, they provide certain guidelines for the development of LTNHRs. To support global deployment of LTNHRs as part of the clean energy transition, China has joined IAEA to make efforts in reaching harmonized SMR standards (IAEA, 2022b). The summary of LTNHR licensing system in China is shown in the Annex Table A1

2.1 Nuclear safety permit system

China implements a full-chain licensing review for nuclear installations; the regulators exert strong safety control over nuclear installations, nuclear materials, nuclear activities, and radioactive materials through full-chain safety licensing and strict technical reviews. For site selection, construction, operation, and decommissioning activities of nuclear power plants, research reactors, nuclear fuel cycle facilities, and radioactive waste treatment, storage, and disposal facilities, phased licensing management throughout the lifecycle is implemented. The review system is risk-oriented and problem-based and is implemented to constantly improve independent safety verifications and verification calculations, probabilistic safety analysis, and risk assessment capabilities.

A nuclear safety license is a legal document issued by a national regulatory authority permitting the applicant to engage in activities related to nuclear power generation with safety implications (such as site selection, construction, operation, and decommissioning). In China, nuclear safety regulators issue opinions reviewing site selection for nuclear power plants, licenses for the construction of nuclear power plants, operating licenses for nuclear power plants, and other approvals, such as approval for decommissioning plans for nuclear power plants (Wang and Liu, 2014). The laws, regulations, and departmental rules and standards related to nuclear installation licensing mainly provide that nuclear installation operators shall apply for a license and comply with the obligation to apply for a license and provide penalties for performing related activities without a license and in violation of legal provisions; additionally, they stipulate the scope of the state's licensing for activities involving nuclear installations and the review responsibilities of relevant agencies.

The Law on Prevention and Control of Radioactive Pollution stipulates that nuclear facility operators shall apply for construction and operating licenses for nuclear installations and complete the approval procedures governing loading and decommissioning before conducting construction, loading, operations, or decommissioning (Article 19) (The National People's Congress of the People's Republic of China, 2003). At the outset of project review, an environmental impact report must be prepared and submitted to the competent authority for review and approval (Article 20). Units that produce, sell, and use radioisotopes and radiation-emitting devices, units that transfer and import radioisotopes and radiation-emitting devices, units equipped with radioisotope meters, and units that produce, sell, and use radioisotopes and accelerators, neutron generators, and radiation-emitting devices containing radioactive material must apply for licenses, complete the registration procedures, and prepare environmental impact assessment documents in accordance with the law (Articles 28 and 29). The establishment of an entity specializing in the storage and disposal of radioactive solid waste must be examined and approved—with a license granted—by the environmental protection administrative department of the State Council. Otherwise, engaging in nuclear-related activities is prohibited, as is providing or entrusting solid radioactive waste to unlicensed entities for storage and disposal (Article 46).

The Nuclear Safety Law stipulates that the state shall establish a nuclear safety licensing system. This system governs nuclear installations, and a nuclear installation operator should apply to the nuclear safety supervision and management department of the State Council, namely the National Nuclear Safety Administration of the Ministry of Ecology and Environment (MEE), for a license for site selection, construction, operation, and decommissioning of nuclear installations (Article 22) (The National People's Congress of the People's Republic of China, 2017). If a nuclear installation operator requests to change the conditions specified in the license document, it shall report to the MEE for approval.

During the site selection phase, the nuclear installation operator must submit review application materials including a Safety Analysis Report for Site Selection of Nuclear Installations to the MEE (Article 23). The MEE shall determine the suitability of the selected site for the nuclear power plant in terms of safety and issue a review opinion regarding whether the selected site meets the nuclear safety requirements (Article 23).

During the construction of a nuclear power plant, the nuclear installation operator shall submit the "Application for Construction of Nuclear Installations," "Preliminary Safety Analysis Report," "Environmental Impact Assessment Document," "Quality Assurance Document," and other relevant information to the MEE before construction (Article 25). The MEE shall review the design principles of the proposed facility determine whether the plant can operate safely after completion. After review and approval, the nuclear installation operators shall obtain a license for the construction of the nuclear installation before beginning construction. After the construction of the nuclear installations is completed, they shall verify whether the facility meets the designed nuclear safety requirements (Article 26).

During the operation of a nuclear power plant, before the nuclear power plant loads nuclear fuel into the core for the first time, the nuclear installation operator shall submit the "Application for Operation of Nuclear Installations," "Final Safety Analysis Report of Nuclear Power Plant," "Quality Assurance Document," "Emergency Plan," and other related materials to the MEE (Article 27). After obtaining a license for the operation of a nuclear installation, the nuclear installation operator shall operate in accordance with the provisions of the license; the validity period of a license for operating a nuclear installation is the design life (Article 27). During the validity period, the MEE is empowered to make reasonable adjustments to the matters stipulated in the license in accordance with the requirements of laws, administrative regulations, and new nuclear safety standards (Article 27). For decommissioning, the nuclear installation operator shall submit the "Application for Decommission of Nuclear Installations," "Safety Analysis Report," "Environmental Impact Assessment Document," "Quality Assurance Document," and other relevant information to the MEE (Article 30). If the nuclear installation must continue to operate after the license for its operation expires, the nuclear installation operator shall, 5 years before the expiration of the validity period, apply to the nuclear safety supervision and management department of the State Council for an extension, and they must demonstrate whether they meet the nuclear safety standards. After review and approval, they can continue to operate (Article 28).

During the decommissioning of a nuclear power plant, the operator of the plant must apply to the MEE for decommissioning permission and submit the "Application for Decommissioning of Nuclear Power Plants," "Safety Analysis Report," "Environmental Impact Assessment Document," "Quality Assurance Document," and other materials as required by law and administrative regulations (Article 30). Entities that provide services in the design, manufacture, installation, and non-destructive testing of nuclear safety equipment for nuclear power plants shall apply to the nuclear safety supervision and administration department under the State Council for a license (Article 36). Operators of nuclear power plants, welding personnel who work on nuclear safety equipment, non-destructive inspection personnel, and other special technical personnel shall obtain corresponding licenses or qualification certificates in accordance with national regulations (Article 37).

In terms of information disclosure and public communication, to ensure the public's right to know, participate, and supervise is honored, the Nuclear Safety Law stipulates that the nuclear safety supervision and management department of the State Council shall, in accordance with the law, disclose administrative licenses related to nuclear safety, safety supervision and inspection reports related to nuclear safety activities, overall safety status, radiation environmental quality, and nuclear accidents, and other information (Article 63). Nuclear safety information disclosed in accordance with the law shall be made available to the public in a timely manner through government notices, websites, and other methods that are convenient for the public to access (Article 65). The MEE has issued the "Nuclear and Radiation Safety Supervision Information Plan" (for trial implementation) and the "Notice on Strengthening the Disclosure of Nuclear and Radiation Safety Information in Nuclear Power Plants" and formulated the "Work Plan for Public Communication on Nuclear and Radiation Safety of the Ministry of Environmental Protection and the Management Measures for Disclosure of Nuclear and Radiation Safety Regulatory Information" to clarify the scope of application, division of responsibilities, content, timing, methods, and channels of information disclosure. (China Nuclear Energy Association, 2011).

2.2 LTNHR licensing system in China

The licensing system applies to the whole process of nuclear power generation from site selection to decommissioning. With the development of technology and on the basis of its experience with large nuclear power plants, a relatively complete nuclear facility licensing regime has been created in China.

2.2.1 SMR and LTNHR licensing regulations concerning siting

Siting involves where to locate a proposed power generation facility, and siting decisions are heavily influenced by various policy considerations. To evaluate the suitability of a proposed site, the following factors should be taken into consideration: 1) the influence of the region on the nuclear power plant, 2) the impact of the nuclear power plant on the area where the plant is to be located, and 3) the influence of population factors (He and Zhao, 1993). LTNHRs, given their flexible design principles, have different siting requirements than do traditional nuclear facilities.

2.2.1.1 Legal system governing nuclear power plant siting

Article 22 of the Nuclear Safety Law stipulates that the siting of nuclear facilities and other related issues are subject to permission from the nuclear safety supervisory authority and the National Nuclear Safety Administration (The National People's Congress of the People's Republic of China, 2003). Article 18 of the Law on Prevention and Control of Radioactive Pollution stipulates that scientific demonstration is a mandatory prerequisite for the siting of nuclear facilities (The National People's Congress of the People's Republic of China, 2003). The general part of the Regulation of the People's Republic of China on the Safety Supervision and Administration of Civil Nuclear Facilities stipulates that nuclear power plants include nuclear electric power plants, nuclear thermal power plants, nuclear steam supply and heating plants, and others (National Nuclear Safety Administration, 1986). As a nuclear power heating plant, LTNHR is a nuclear facility requiring strict supervision and management, and LTNHRs must comply with the relevant licensing system for construction and operation.

The HAF101-1991 Safety Regulations for Siting of Nuclear Power Plants is the general series of nuclear safety department regulations. Per these regulations, the influence of relevant factors should be investigated during the whole lifetime of a nuclear power plant, and further, the safety of nuclear power plants built on suitable sites should be guaranteed through the design, construction, commissioning, operation, and decommissioning phases (National Nuclear Safety Administration, 1991). Scientific siting is closely related to the acceptability of the site, and the purpose of investigating the population factor is to minimize the harm to people when serious incidents occur. In Section 3 of the Safety Regulation, the selection criteria for nuclear power plant sites are described in detail. With regard to the population factor, the foreseeable evolution of natural and human factors affecting the safety of the nuclear power plant in the area where the nuclear power plant is located must be evaluated, and further, these factors must be monitored throughout the lifetime of the nuclear power plant, especially the population growth rate and population distribution characteristics.

The HAD series is the Nuclear Safety Guidelines issued by the National Nuclear Safety Administration and serves as a guiding document for meeting the requirements of laws and regulations. HAD 101/03 Population Distribution in Nuclear Power Plant Siting and

Evaluation is the explanation and supplement of HAF 101 mentioned above, and it clearly stipulates that "according to the international nuclear energy development experience, with the accumulation of experience and technological progress, it is gradually feasible to select the plant site in areas with high population density, but priority should be given to areas with low population density" (National Nuclear Safety Administration, 1987) Article 5.7 of GB 6249-2011 Regulation for Environmental Radiation Protection of Nuclear Power Plant further requires that nuclear power plants should be built as far away from big cities as possible in areas with relatively low population density. There should be no towns with more than 10,000 people within the planning restricted area, and there should be no towns with more than 100,000 people within a radius of 10 km of the plant site (Ministry of Ecology and Environment of the People's Republic of China).

The T/BSRS 022-2020 Technical Specification of Identification of Exclusion Area and Planning Restricted Area for SMRs is intended to promote the fast development of SMRs. The technical specification provides that SMRs can be located in areas with high population density but should be kept a certain distance from concentrated residential areas with more than 10,000 residents (Beijing Radiation Safety Research Association, 2020). According to the literal interpretation, reactors should be at least 2 km away from towns with more than 10,000 inhabitants, and the population factor should be included in the arrangement of emergency plans.

2.2.1.2 Siting requirements in LTNHR technical documents

Four technical documents promulgated in 1996 govern LTNHRs. At the siting stage, the population factor must be taken into account. Compared with traditional nuclear power plants, LTNHRs have looser requirements in this regard. The HAF J0059-1996 Safety Criteria for Siting of LTNHR govern the supervision and management of safety and radiation protection of LTNHRs and account for the technology's specific characteristics (National Nuclear Safety Administration, 1996a). The HAF J0060-1996 Radiation Protection Safety Standard for LTNHR Operation does not have a population factor provision but requires radiation dose control within 50 km of population centers (National Nuclear Safety Administration, 1996b). The HAF J0061-1996 Radiation Protection Safety Criterion for LTNHR Operation states that LTNHRs should be built in the vicinity of a city or in an area with a large population and that its design should have inherent safety and passive safety characteristics (National Nuclear Safety Administration, 1996c). The HAF J0062-1996 Safety Guidelines for Radioactive Waste Management of LTNHR also specify that LTNHR should be built near densely populated areas and that, consequently, they should be managed strictly (National Nuclear Safety Administration, 1996d).

2.2.2 LTNHR licensing regulations concerning construction

After site licensing, the nuclear facility enters the stage of construction licensing. Here, the delimitation of EPZ and allocation of emergency preparedness funds are two critical aspects of construction licensing. The delimitation of the EPZ is formally implemented in the construction licensing stage, and the maintenance and emergency plan implementation drills are conducted in the operation stage until the end of the life of the nuclear power plant.

2.2.2.1 Delimitation of EPZ in construction licensing

The responsible development of the nuclear power industry is based on the safe operation of nuclear power plants. The EPZ is the key area for the prevention and management of nuclear safety controls. Article 21 of the Nuclear Safety Law stipulates that the people's governments of provinces, autonomous regions, and municipalities directly under the Central Government shall delimit restricted areas surrounding nuclear power plants and other major nuclear facilities and that it is prohibited to build a facility producing or storing flammable, explosive, or corrosive materials that might threaten the safety of a nuclear facility or a populous venue within the planned restricted area. This means that there is also a need to restrict activities in the planned restricted areas, and the Nuclear Safety Act also provides for penalties for violations.

The GB6249-2011 Regulations for Environmental Radiation Protection of Nuclear Power Plant govern delimitation and require that exclusion and planned restricted zones be set around the nuclear power plant; the distance between the boundary of the exclusion zone and the reactor shall not be less than 500 m. (Ministry of Ecology and Environment of the People's Republic of China). The radius of the planned restricted area shall not be less than 5 km. The regulations also require that nuclear power plants be far away from large cities. There should be no towns with more than 10,000 residents within the planned restricted area, and there should be no towns with more than 100,000 inhabitants within a radius of 10 km of the plant site (Article 5.6, Article 5.7). The scope of the exclusion zone shall not be less than 500 m, the radius of the planned restricted area shall not be less than 5 km, and the scope of EPZ shall be at least 10 km.

The GB/T 17680.1-2008 Criteria for Emergency Planning and Preparedness for Nuclear Power Plants specify criteria for nuclear power plant emergency planning and suggest the scope of emergency planning for PWR nuclear power plants. These guidelines adopt the general classification of large reactors, which is according to irradiation form; namely, 7–10 km is the ingestion EPZ, and 3–5 km is the plume EPZ (General Administration of Quality Supervision and Inspection and Quarantine of the People's Republic of China and Standardization Administration, 2008).

T/BSRS 022-2020 clarifies the differences in safety, economics, and possible harm between small reactors and large reactors. It provides that the planned restricted area can also be stipulated differently and that the scope of the exclusion area and planned restricted area can be reduced compared with large nuclear power plants (Article 4.2). Specifically, the technical specification provides that the exclusion area of small reactors be set within 100 m and the planned restricted area be within 1 km (Beijing Radiation Safety Research Association, 2020).

Among the four special documents concern LTNHRs, the HAF J0059-1996 specifically provides for the setting of the EPZ during construction, and section 5.2.1 stated that an LTNHR does not require an off-site emergency area in case of accident and that the radiation exposure to the public must conform to the national regulations and be below the acceptable threshold (National Nuclear Safety Administration, 1996a). Additionally, the safety level of a cryogenic heating reactor should be such that an off-site emergency planning area is not necessary, and the construction should be simplified. An emergency planning area in the narrow sense should be unnecessary, and only the non-residential area and planned restricted area should be set. The specific ranges for these are 250 m and 2 km, respectively.

2.2.2.2 Regulations on emergency preparedness funds during construction

Emergency preparedness funds for the EPZ must be prepared at the time of construction, and the preparation must be based on the planning of the emergency planning area. Relevant provisions are mainly found in two documents. Article 55 of the Nuclear Safety Law stipulates that the provincial people's government is responsible for the off-site emergency plan and the nuclear facility operator is responsible for on-site plans. Article 34 of the Regulation on Emergency Management of Nuclear Accidents in Nuclear Power Plants directly stipulates that the on-site nuclear accident emergency preparedness funds shall be contributed by the nuclear power plant and included in the investment budget and operating cost of the nuclear power plant project; the responsible parties for off-site accidents are the operators and local people's governments. Therefore, the provider of on-site emergency funds is the operator, who should allocate the appropriate funds when the planning and construction of the emergency planning area are implemented.

2.2.3 Monitoring and supervision of LTNHR in operation stage

In the operation stage of a nuclear power plant, the monitoring of radioactive efflux emissions under normal operating conditions is a necessary measure to ensure nuclear safety. Article 6.6 of GB6249-2011 requires that the total annual emissions of a nuclear power plant should be controlled and measured on a quarterly and monthly basis; the total annual emissions in each quarter should not exceed half of the approved total annual emissions. Total monthly emissions should not exceed one-fifth of the approved annual emissions (Ministry of Ecology and Environment of the People's Republic of China). In HAF J0060-1996, it is stipulated that the emissions of each LTNHR should be 2.5 times lower than the emissions stipulated in GB6249, which sets the management limit for LTNHRs. Considering the large amount of emissions produced during the maintenance stage, emissions are allowed to be held to less than 2 times of the normal monthly average at this stage (National Nuclear Safety Administration, 1996b).

2.2.4 LTNHR planning: Information disclosure and public participation

The regulation of information disclosure and public participation is one of the safety measures to ensure the operational safety of nuclear power plants. Given the history of widespread social resistance to the use of nuclear energy, public participation is vital to project acceptance. Laws and regulations such as the Environmental Protection Law, the Environmental Impact Assessment Law, and the Environmental Protection Management Regulations for Construction Projects stipulate that site selection, information disclosure, explanation of the proposed project, and public consultation are required before the construction of nuclear facilities. The Law on the Prevention and Control of Radioactive Contamination provides the public the right to report and complain about problems in the operation of nuclear facilities (The National People's Congress of the People's Republic of China, 2003). According to the rules and regulations, the obligation to disclose information starts after site selection but before the construction of nuclear facilities.

The Nuclear Safety Law also requires governments and operators of nuclear facilities to make disclosures of nuclear safety information in accordance with the law to ensure the public's right to know and right to participate are honored. Article 66 stipulates that the operator of a nuclear facility shall solicit the opinions of stakeholders on major nuclear safety issues of public interest through questionnaires, hearings, discussion meetings, symposia, or other forms/forums, and provide feedback in an appropriate form. The relevant governments shall hold hearings, discussion meetings, and symposia on major nuclear safety issues that affect the public interest or solicit opinions from interested parties in some other form and provide feedback in an appropriate manner. Therefore, in China, the relevant laws and regulations stipulate that nuclear safety information related to the construction and operation of nuclear facilities must be disclosed to the public and that public opinion must be sought.

3 Incompatibility between existing regulations and LTHNR operation

The preceding review of laws, regulations, and standards governing the process of nuclear facility site selection, construction, operation, and public participation demonstrates that China has established a relatively mature licensing regime for large nuclear reactors after decades of development and practice. However, the existing legal norms for large nuclear reactors are not necessarily fully compatible with LTNHR projects, and its legal system specifically for SMR is still in its infancy.

3.1 Incompatibility due to lagging legal system

In China, LTNHRs experienced a period of rapid development before the Chernobyl nuclear accident in 1986. A series of technical documents concerning LTNHR technology were issued worldwide in the middle and late 1990s. China's regulations, however, have not been revised in light of the current LTNHR technology. A legal regime comprising laws, administrative regulations, departmental rules, guidance documents, and technical documents governs LTHNR licensing, but the existing legal regime was mainly devised to meet the issues associated with large reactors (Nuclear Energy Agency, 2021a). Although SMR technology is becoming popular, the existing licensing rules are outdated and ignore the characteristics of SMRs and LTNHRs. The legal regime is thus impeding the promotion, application, and implementation of SMRs and LTNHRs (Ramana et al., 2013).

At the level of departmental regulations and guidance documents, some regulatory standards for SMRs have been issued, such as the pilot version of the Safety Evaluation Principles for Small Pressurized Water Reactor Nuclear Power Plant released in 2016 (National Nuclear Safety Administration, 2016) and the T/BSRS 022-2020 Technical Specification for the Division of Non-Residential Areas and Planning Restricted Areas for Small Nuclear Power Plants released in 2020 (Beijing Radiation Safety Research Association, 2020). These provide technical regulations for SMRs but still fail to consider the specific characteristics of LTNHRs and cannot be fully applied to LTNHRs in practice. Moreover, these documents do not have legal effect, as they are only technical opinions of experts or recommended suggestions, and the contents are often translations of IAEA technical materials, which have also been lagging to keep up with the fast technology development of LTNHRs.

Additionally, as the deployment of the LTNHRs is based on many technical documents, the low legal rank of technical documents directly affects the effectiveness of law enforcement. Also, the supervision authorities are often confronted challenges in practice. For example, government and regulatory authorities oftenly have too much discretion in the approval or supervision procedure due to the lack of detailed regulation of LTNHRs. Insufficient mandatory legal norms and unified standards also affect the degree to which the technical documents are accepted by the public. In addition, the development of LTNHRs, which also aims to promote nuclear energy utilization, requires effective public communication and a high level of stakeholder engagement. China's existing LTNHR regulatory system, however, is not comprehensive and detailed enough to ensure sufficient information disclosure and public participation. Only when the affected residents have sufficient information regarding the deployment of LTNHRs, can eventually promote the smooth development of LTNHRs.

3.2 Inapplicability of existing regulations to LTNHRs

First, there is an unfitness during site selection. From the perspective of the laws and regulations applicable to traditional nuclear power plants, the population factor is critical during the site selection process. Choosing a remote site location is considered an effective approach to avoid risk to people. Due to the developed technical standards of LTNHRs, which have a better safety profile, the population factor in site selection has tended to be downplayed. Effective emergency management plans are deemed more critical than a remote location. For regulations to apply the same standards to the inherently safer LTNHR technology as to traditional facilities is misguided, and people may misapprehend that LTNHRs are no safer than traditional plants.

Second, there is an unfitness during construction stage. Designating the emergency planning area is the main economic constraint for LTNHRs. But there are other problems. First, the transmission lines from a remote location are expensive. Moreover, LTNHRs lose heat transmission capacity over long distances; this is different than the case with traditional plants, where high-voltage transmission has minimal loss (Lv et al., 1984). Then, there is the issue that the emergency planning area is, when applying the traditional regulations, typically too large, which is economically wasteful. These problems must be addressed by better regulations. Emergency funding is another critical issue. Given the safety profile of LTNHRs, the EPZ should be downsized; with a smaller EPZ, less funding is necessary as well. This funding and area designation better match the safety profile of LTNHRs.

Third, there is an unfitness during operation stage. During operations, LTNHRs are fundamentally more environmentally friendly than older systems. Moreover, because they are designed for generating heat rather than electricity, they operate with seasonal variability. Hence, the emissions in winter will outweigh those in summer, and thus, regulations should establish standards that flexibly consider the yearly aggregate rather than smaller units of time (i.e., low summer emissions will offset excessive winter emissions).

Fourth, there is a conflict between information disclosure and public participation. According to the current right-to-know system, the site selection process is not regarded as a "major nuclear safety matter involving public interests" and is not disclosed to the public or solicited public opinions. This is actually problematic because people remain uneasy about nuclear power; consequently, having information disclosure at the very outset of the process may serve to allay these concerns and promote project development.

4 Suggestions to improve LTNHR licensing system in China

Regulatory reforms can promote the effective deployment of LTNHRs. Their inherent safety features and multimodule deployment configurations result in specific failure modes and consequences that are relatively new for regulators. Whether licensing regulatory frameworks are flexible enough to adapt to LTNHRs without necessitating major modifications to their design is a crucial question influencing the development of LTNHRs. This section proposes suggestions for improving the licensing system for LTNHRs in China to promote the development of LTNHRs in China in the future.

4.1 Promulgating and improving laws and regulations concerning LTNHRs

Due to the lack of laws and standards on nuclear energy heating in China, it is therefore urgent to formulate a series of laws and standards so as to provide sufficient legal support for LTNHR development. It is significant to modify relative regulations which have obviously conflicted with the characteristics of LTNHR so as to promote the smooth deployment of LTNHR projects. First, it is necessary to devise exclusive LTNHRs regulations as soon as possible, taking account of the differences between traditional nuclear power plants, SMRs, and LTNHRs. It is necessary to update regulations that were tailored to traditional nuclear power plants. Key regulations governing SMRs should be modified to apply to LTNHRs, and then, specific regulations for LTNHRs can be built on this foundation. Of particular relevance would be SMR regulations concerning facilities generating less than 300 MW. The scientific and timely update of the legal system is particularly crucial to further promote the development of LTNHRs in China.

Multiple standards should be designed and implemented in the licensing regime to meet the regulatory requirements of different LTNHRs. Although the main function of LTNHR is heating in winter, the demand for LTNHRs is not only during the heating period in winter in the northern provinces of China. LTNHRs can also play important roles in grid power supply, seawater desalination, inland brackish water treatment, and other applications (Ke et al., 2020). This diversity of applications requires a more refined licensing system, as many LTNHRs would operate throughout the year.

Another key target of reform is the regulations regarding siting requirements for LTNHRs; these should be timely updated or revised. As noted, LTNHRs are safer than traditional facilities and pose less risk to nearby inhabitants. Engaging the local public early in design could inform the decision whether a site is too close to a population center (Cao et al., 2014). Ideally, the distance of LTNHRs from population centers could be 2 km, assuming the area is not particularly densely populated. Targeting areas with favorable opinions to nuclear power would be another wise strategy at the planning stage. Avoiding public backlash or "not in my backyard" grievances would help expedite the rest of the process.

Although the LTNHR technology has reached a relatively safe level (Zhang and Zheng, 2021), directly merging the planned restricted area and the EPZ may hinder the implementation of the LTNHR projects. The three-area planning model outlined in T/BSRS 022-2020 is comparatively more scientific and reasonable; it stipulates that the distance of a facility from a non-residential area be not less than 100 m, the distance of the planned restricted area be generally less than 1 km, and the distance of the EPZ be about 2 km (Beijing Radiation Safety Research Association, 2020).

The allocation of emergency funds also requires reform. Presently, the burden falls on the operator, but that makes projects economically unattractive. Given that LTNHRs have superior safety profiles and the risk of off-site accidents is dramatically lower than that of traditional facilities, the government being responsible for off-site accidents largely leaves them responsible for a remote possibility; this is poor resource allocation. Instead, the government and the operator should proportionally share emergency funding for the more likely—though still highly unlikely—occurrence of on-site incidents.

4.2 Enhancing information disclosure and public participation

Given that construction and operations will be closer to the public and residential areas, it is likely that LTNHRs will face a somewhat different set of challenges related to public engagement than those faced by traditional large reactors. Successful siting of LTNHRs especially will require close attention to the preferences of host communities. As a result, it is critical that countries, including and especially China, considering the deployment of LTNHRs determine how public engagement efforts for LTNHRs might need to differ from those adopted for large reactors.

Historically, opposition to nuclear power has stemmed from the possible harm from a nuclear accident. (China Energy network, 2009). Appropriate risk–benefit communication needs to be delivered to the public; information needs to be provided that is accessible and understandable to non-expert members of the public. In this way, the public can rationally consider a project rather than relying on fear and hearsay. Sufficient information should be disclosed to ensure public participation in site selection; the site selection process should be open to the public, and their opinions should be solicited—this is an important element to ensure nuclear safety. Then, after the public assents to a project, information and public participation should be made available throughout the LTNHR operations. The government and operators must conduct effective science communication regarding LTNHRs. Operators need to be assigned more responsibility for communicating with the public in the licensing process, and this should also be regulated and codified in law. Local and regional job creation is always a popular angle for project communications; additionally, if there is other economic benefit, such as lower electricity rates, this should be highlighted as well.

4.3 Improving international collaboration by harmonizing licensing frameworks

Regulatory regimes may vary significantly among countries. Each country ensures that safety requirements are aligned with national interests and current regulatory practices while preserving public confidence in the decisions of the regulatory body. There are generally three levels of regulations to harmonize: legal frameworks (governments), licensing and regulatory guidance (nuclear regulators), and codes and standards of practice (industry) (Nuclear Energy Agency, 2020). Harmonization in licensing requirements and licensing processes for LTNHRs could facilitate the deployment of these SMR designs in countries lacking regulatory regimes. Local procurement of components could also be facilitated, which would in turn enable the creation of global markets and global supply chains. As such, harmonization is crucial for widespread proliferation of this technology. While complete harmonization might be unrealistic, efforts should continue to achieve harmonization in areas where meaningful common regulatory positions can be achieved. Moving toward a multinational licensing approach, encouraging cooperating in the licensing of a design under different regulatory regimes, and ensuring a sufficient level of regulatory sovereignty at the national level are all key agenda items. Nuclear Energy Agency (NEA) explorations of multilateral licensing coordination, bilateral collaborations, and joint safety evaluations, such as were conducted under the Multinational Design Evaluation Programme, should be considered (Nuclear Energy Agency, 2021b).

LTNHRs represent an opportunity for the early development of international collaboration for harmonization of licensing frameworks as well as codes and standards. These topics have already been extensively discussed in the context of large reactors, and the experience gained can be applied to LTNHRs. At the level of industrial codes and standards harmonization, the World Nuclear Association Cooperation in Reactor Design Evaluation and Licensing Working Group has made significant progress (World Nuclear association, 2022). The harmonization of licensing regimes of LTNHRs can also be based on prior experience. Advancements can be made in harmonization by leveraging existing collaborative frameworks for large reactors. One example is the dedicated licensing of SMR modules applicable to different sites, which are approved in different countries under reciprocal agreements. Such an approach would help capture the benefits of standardization, both in terms of learning by doing from serial production as well as in terms of reducing the fixed costs associated with licensing.

5 Conclusion

Although significant progress has been made in the development of LTNHRs, many challenges remain. As a new commercial form of nuclear reactor, LTNHR regulation depends on existing traditional nuclear reactor standards, which are outmoded and inappropriate for LTNHR application. LTNHRs take longer to construct than traditional coal heating facilities, and this causes low acceptance among the public. With the heating network extending over 15 km, the relatively high cost of LTNHRs also impedes the development of this technology. This article has evaluated the legal regime for licensing and identified its weak spots that are most inapplicable to LTNHRs; additionally, this article has identified areas in which LTNHR licensing can be substantially improved. For instance, public outreach provisions, siting rules, area restrictions, and responsibility for emergency funding all emerged as issues ripe for regulatory change.

In general, the current licensing frameworks relies on the extensive experience base accumulated through regulating large reactors. The SMR system, however, differs in important respects from such large reactors, and appropriate regulations are needed to expedite implementation of what promises to be a valuable technology for meeting carbon reduction goals and controlling the cost of heating. Overall, China is in the initial stage of SMR development, and the regulatory framework is underdeveloped. This article examined the laws, regulations, and standards in the Chinese licensing system for SMRs and LTNHRs and further explained that a series of standards for LTNHRs were introduced in the 1990s; this period of time marked the early stage of the development of LTNHRs, and thus, some regulations are not compatible with the current technology of LTNHRs. In addition, LTNHRs cannot be implemented effectively in practice due to legal hurdles. The regulation system is still based on the standard designed for conventional traditional large reactors and have not been modified to better accommodate LTNHRs.

The development and initial deployment of LTNHRs require a concerted effort between government regulators and industry. Government support for LTNHR deployment must encompass the provision of long-term policy support, which facilitates mobilization among the relevant stakeholders at the government, private, and community levels. Government should also design a more appropriate licensing regime to enable and expedite deployment and construction of LTNHRs. These initiatives can take place through existing or dedicated legislative frameworks that integrate LTNHRs development efforts into national energy policy frameworks.

Beyond current national efforts, the international nature of the LTNHR market provides a rationale for coordination at the international level; in particular, the development of an international licensing framework for LTNHRs is urgently needed. From a global perspective, it is necessary to harmonize regulatory standards in relation to a particular LTNHR design or family of designs. The harmonization of international standards on licensing is crucial for the safe and effective widespread deployment of LTNHRs. It helps strengthen regulatory collaboration and build common ground on policy regulation issues. Future projects can benefit from international collaboration, exchange of information about lessons learned, and difficulties and best practices identified by early adopters through public engagement with local communities. China can cooperate with other countries in developing international standards and assisting other countries to develop national standards that conform. China can also introduce its regulatory standards and construction experience to states and regions along the Belt and Road and support other developing countries. This will further promote global international cooperation in developing LTNHRs to realize the carbon neutrality goal and combat climate change collectively (European Nuclear Safety Regulators Group, 2009; Sainati et al., 2015; William and Cubbage, 2015).

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

BL is the first author and contributes most to the paper. JL is the corresponding author of the paper and LS helps them translates the legislation and regulations from Chinese to English.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix

TABLE A1 China's Licensing System of LTNHR.

Licensing System	Laws	Administrative Regulations	Departmental Regulation and National Standards	Technical Documents	Organization Standards
	1. Law of Prevention and Control of Radioactive Contamination	1. Safety Supervision and Administration of Civil Nuclear Facilities	1. HAD 101/03[2]	1. HAF J0059-1996[5]	T/BSRS 022-2020[9]
	2. Nuclear Safety Law	2. Regulations on Emergency Management of Nuclear Accidents in Nuclear Power Plants	2. GB 6249-2011[3]	2. HAF J0060-1996[6]	
		3. HAF101-1991[1]	3. GB/T 17680.1-2008[4]	3. HAF J0061-1996[7]	
				4. HAF J0062-1996[8]	
Siting Stage	1. Law of Prevention and Control of Radioactive Contamination (Article 18)	1. Safety Supervision and Administration of Civil Nuclear Facilities	1. HAD 101/03	1. HAF J0059-1996	T/BSRS 022-2020
	2. Nuclear Safety Law (Article 22)	2. HAF101-1991	2. GB 6249-2011	2. HAF J0060-1996	
			3. GB/T 17680.1-2008	3. HAF J0061-1996	
				4. HAF J0062-1996	
Construction Stage	Law of Prevention and Control of Radioactive Contamination (Article 21,55)	Regulations on Emergency Management of Nuclear Accidents in Nuclear Power Plants	1. GB 6249-2011	HAF J0059-1996	T/BSRS 022-2020
			2. GB/T 17680.1-2008		
Operation Stage	N/A	N/A	GB 6249-2011	HAF J0060-1996	N/A
Information Disclosure and Public Participation	1. Law of Prevention and Control of Radioactive Contamination (Article 33)	N/A	N/A	N/A	N/A
	2. Nuclear Safety Law (Article 66)				

[1]HAF101-1991 Safety Regulations for Siting of Nuclear Power Plants (《核电厂厂址选择及评价的人口分布问题》).
[2]HAD 101/03 Population Distribution in Nuclear Power Plant Siting and Evaluation (《核电厂厂址选择及评价的人口分布问题》).
[3]GB 6249-2011 Regulation for Environmental Radiation Protection of Nuclear Power Plant (《核电厂环境辐射防护规定》).
[4]GB/T 17680.1-2008 Criteria for Emergency Planning and Preparedness for Nuclear Power Plants The Dividing of Emergency Planning Zone (《核电厂应急计划与准备准则 应急计划区的划分》).
[5]HAF J0059-1996 Safety Criteria for Siting of LTNHR (《低温核供热堆厂址选择安全准则》).
[6]HAF J0060-1996 Radiation Protection Safety Standard for LTNHR Operation (《低温核供热堆运行辐射防护安全准则》).
[7]HAF J0061-1996 Radiation Protection Safety Criterion for LTNHR Operation (《低温核供热堆核事故应急准备安全准则》).
[8]HAF J0062-1996 Safety Guidelines for Radioactive Waste Management of LTNHR (《低温核供热堆放射性废物管理安全准则》).
[9]T/BSRS 022-2020 Technical Specification of Identification of Exclusion Area and Planning Restricted Area for SMRs (《小型核动力厂非居住区和规划限制区划分技术规范》).