A Glimmer Through Shut Door

Assessment of Advanced Nuclear Reactor Technologies on North Korea Denuclearization

November 2024 REC-PP-21

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Research Center for Nuclear Weapons Abolition, Nagasaki University(RECNA)

長崎大学核兵器廃絶研究センター（RECNA）

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はじめに

本 RECNA Policy Paper は、人材育成を目的とした、次世代の研究者による Policy Paper の第２弾（RECNA-PP-19 に続く）である。Anthony Dai 氏は、米 James Martin Center for Nonproliferation Studies（CNS）, Middlebury Institute of International Studies at Monterey の大学院学生で、RECNA に短期研究スタッフとして派遣され、2024 年６月～８月の２か月間、研究活動に従事した。Dai 氏は、RECNA における北東アジア非核化プロジェクトに参加し、本 Paper は、その２か月間の研究活動の成果の一環として、まとめたものである。

長崎大学核兵器廃絶研究センター
センター長・教授　吉田文彦

Introduction

This RECNA Policy Paper is the second series of Policy Paper for a researcher of next generation (following RECNA Policy Paper No. 19). Mr. Anthony Dai, a graduate student at James Martin Center for Nonproliferation Studies (CNA), Middleburry Institute of International Studies at Monterey, came to RECNA and worked as a Research Assistant, joining the project on De-nuclearization of Northeast Asia, from June to August 2024. This Policy Paper is one of the outputs of his research activities during his stay at RECNA.

Research Center for Nuclear Weapons Abolition (RECNA)
Director, Professor
Fumihiko Yoshida

Abstract

The denuclearization of the Democratic People's Republic of Korea (DPRK) has been a persistent challenge, compounded by geopolitical tensions and the nation's economic and military strategies. This paper explores the potential of leveraging advanced nuclear reactor technologies to support a comprehensive denuclearization framework. Innovations such as Small Modular Reactors (SMRs), High-Temperature Gas-cooled Reactors (HTGRs), and advanced fuel cycles, including High-Assay Low-Enriched Uranium (HALEU), are analyzed for their potential to meet DPRK's energy needs while reducing proliferation risks. Key findings reveal that SMRs and HTGRs, with their modular designs, enhanced safety features, and reduced proliferation risks, could offer scalable and secure energy solutions. These technologies may serve as economic incentives to encourage the DPRK's participation in denuclearization talks. However, significant challenges remain, including the dual-use nature of nuclear technologies, risks associated with reprocessing, and the geopolitical complexities of implementing international safeguards in the DPRK. The paper underscores the importance of integrating these technologies within a robust diplomatic and regulatory framework to prevent diversion for military purposes. Policy recommendations focus on adopting a phased approach to transition the DPRK toward a nuclear latency state, emphasizing international cooperation, stringent safeguards, and economic integration. Leveraging lessons from frameworks such as the Joint Comprehensive Plan of Action (JCPOA), the study advocates for balancing incentives with rigorous verification mechanisms to ensure compliance. This multifaceted strategy aligns technological advancements with non-proliferation objectives, offering a pathway toward sustainable energy development and regional stability while addressing the challenges of denuclearization.

朝鮮民主主義人民共和国（DPRK）の非核化は、地政学的緊張と国家の経済・軍事戦略によって複雑化し、根強い課題となっている。本稿では、包括的な非核化の枠組みを支援するために、先進的な原子炉技術を活用する可能性を探る。小型モジュール炉（SMR）、高温ガス炉（HTGR）、高濃度低濃縮ウラン（HALEU）を含む先進燃料サイクルなどの革新技術を分析し、核拡散リスクを低減しながら北朝鮮のエネルギー需要を満たす可能性を探る。その結果、SMR と HTGR は、モジュール設計、強化された安全機能、核拡散リスクの低減により、柔軟な能力拡大と安全なエネルギー供給を提供できることが明

らかになった。これらの技術は、朝鮮民主主義人民共和国の非核化交渉への参加を促す経済的インセンティブとして機能する可能性がある。しかし、原子力技術の軍民両用性、再処理に伴うリスク、朝鮮民主主義人民共和国における国際保障措置の実施における地政学的複雑性など、重大な課題も残されている。本稿は、軍事目的への転用を防ぐため、強固な外交的・規制的枠組みの中でこれらの技術を統合することの重要性を強調している。 政策提言は、国際協力、厳格な保障措置、経済統合を重視し、北朝鮮を現在の核保有状態から潜在的核能力保有状態に移行させるための段階的アプローチを採用することに焦点を当てている。イランとの共同包括行動計画（JCPOA）のような枠組みからの教訓を生かし、コンプライアンスを確保するための厳格な検証メカニズムとインセンティブのバランスをとることを提唱している。この多面的な戦略は、技術の進歩と核不拡散の目的を一致させ、非核化の課題に対処しながら、持続可能なエネルギー開発と地域の安定に向けた道筋を示すものである。

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I. Introduction

The Democratic People's Republic of Korea (DPRK) has long been a focal point of international concern due to its nuclear weapons program. Since the 1990s, North Korea has conducted several nuclear tests, leading to global condemnation and numerous attempts at denuclearization through diplomatic channels. The Agreed Framework of 1994,[1] the Six-Party Talks from 2003 to 2009,[2] and more recent summits between the DPRK and the United States have all sought to curb North Korea's nuclear ambitions with varying degrees of success. Despite these efforts, the DPRK has continued to advance its nuclear capabilities, underscoring the persistent challenge of achieving complete denuclearization.

The Russia-Ukraine conflict that began in 2022 has significantly impacted global economic and geopolitical landscapes, creating unique challenges and opportunities for the DPRK. On one hand, North Korea faces increased economic isolation due to its overt support for Russia. This alignment has resulted in stricter sanctions and further alienation from the global economy. On the other hand, this economic hardship is juxtaposed with the benefits derived from a closer military and economic relationship with Russia.[3] The DPRK has seen a boost in its economic activities through armament orders and military trade with Russia, providing a critical lifeline to its struggling economy. This dual economic reality places North Korean decision-makers in a complex situation. The immediate economic gains from supporting Russia's wartime efforts are evident, yet the long-term sustainability of such gains is uncertain. The need to maintain economic prosperity beyond the conflict is likely a significant concern for the DPRK leadership. This scenario may open a window for renewed discussions on denuclearization. The potential for economic incentives and integration into the global economy could be leveraged to encourage North Korea to reconsider its nuclear stance.

This research aims to explore how recent advancements in nuclear technology can be aligned with efforts to denuclearize the DPRK. By examining the potential of advanced nuclear reactor technologies, such as Small Modular Reactors (SMRs), High-Temperature Gas-cooled Reactors (HTGRs), and advanced nuclear fuel cycles, this research seeks to understand how these innovations could support a comprehensive denuclearization strategy. SMRs, with their smaller size and enhanced safety features, could offer a flexible and potentially more secure energy solution. HTGRs, known for their high efficiency and safety characteristics, may provide another viable option for sustainable energy production. Additionally, the adoption of advanced nuclear fuel cycles and High-Assay Low-Enriched Uranium (HALEU) in the future may require additional attention to ascertain the risks associated with nuclear proliferation.

Exploring the role of these technologies in the context of DPRK's denuclearization involves assessing their technical capabilities, safety features, and potential for proliferation resistance. To identify strategies, it is necessary to address not only North Korea's energy needs,[4] which constitute long-term effective leverages, but also contribute to regional and global security by reducing the risks associated with nuclear weapons proliferation. This comprehensive approach aims to align technological advancements with diplomatic efforts, creating a multifaceted strategy for denuclearization that incorporates economic, political, and technological dimensions.

II. Recent Advancements in Nuclear Technology

A. Small Modular Reactors

Proponents of Small Modular Reactors (SMRs) argue that SMRs represent a significant innovation in nuclear technology, characterized by their smaller size and modular design compared to traditional large-scale reactors. SMRs typically produce up to 300 megawatts of electrical power per unit,[5] making them more suitable for a variety of applications than conventional large (1,000 MWe) reactors, including electricity generation in remote areas and industrial power supply. It is also argued that their modular nature allows for factory fabrication, leading to cost reductions, enhanced quality control, and shorter construction times. These reactors are also designed with enhanced safety features, such as passive safety systems that rely on natural physical processes to maintain safety without human intervention or external power sources.

One of the critical considerations in evaluating SMRs is their potential for proliferation resistance, which refers to the ability of a nuclear technology to resist the diversion of nuclear materials for weaponization. According to a study done by OECD/NEA, SMRs can offer several advantages.[6] Firstly, many SMR designs continue to employ low-enriched uranium (LEU) as fuel, which is less suitable for weaponization compared to plutonium used by other advanced reactors such as Fast Reactor. Secondly, several SMR designs emphasized on its on-site refueling-free features which alleviate the safeguard burden and minimize the possibility of fuel exposure. Additionally, the smaller size and modular nature of SMRs allow for more stringent security and monitoring measures, reducing the risk of unauthorized access to nuclear materials.

However, the proliferation resistance of SMRs is not without challenges. Some SMR designs, such as fast-spectrum reactors, have the potential to produce significant amounts of plutonium, which could be used for nuclear weapons. For instance, the long-lived core designs, which do not require refueling for decades, can accumulate large quantities of plutonium. A study by Ramana (2014)[7] highlights that a 200 MWe SMR with a long-lived core could generate approximately 2.8 tons of plutonium over its operational life, with about 80% being plutonium-239, a fissile isotope suitable for weapons production, compared to about 60% fissile plutonium in typical spent fuel from conventional LWRs. Despite its lower production by individual units, SMR in many configurations is installed in multiple-unit groups. Such a finding did make SMRs an attractive target for reprocessing to obtain weaponizable plutonium and, therefore, highlighted the need for a more comprehensive safeguarded fuel cycle, especially reprocessing technologies and facilities with the interest of building a closed fuel cycle or directly weaponizable fuel. Another significant proliferation risk is the potential for cyber-attacks on SMRs. As digital technologies become increasingly integrated into nuclear reactor operations to improve reactor safety and performance and reduce the operational cost of SMRs by reducing the operators, the cybersecurity of SMRs is a crucial aspect of their proliferation resistance. Cyber-attacks on nuclear facilities can have severe consequences, including the theft of sensitive information, sabotage of reactor operations, and unauthorized access to nuclear materials. SMRs, with their advanced digital control systems, are not immune to these threats. Ensuring robust cybersecurity measures is essential to protect these reactors from potential cyber-attacks that could compromise their safety and security.

The ability of SMRs to contribute to non-proliferation efforts largely depends on the specific design and the operational context. For example, reactors that require less frequent refueling pose a lower risk of material diversion during the refueling process. Conversely, integrated designs that are more challenging to inspect could increase proliferation risks. This duality is evident in the various SMR models currently being developed. For instance, designs such as the Integral Pressurized Water Reactor (iPWR) and the Long-Lived Core SMR (LLC-SMR) each present unique proliferation risks.[8] The iPWR, while reducing uranium and enrichment requirements, results in higher cumulative plutonium production compared to standard reactors, potentially increasing proliferation risks. In contrast, using safeguards by design(SBD) approach and additional security measures offered an option to mitigate these risks. IAEA plays a crucial role in this regard, providing comprehensive safeguards and verification mechanisms to ensure that nuclear materials are not diverted for non-peaceful purposes. Effective implementation of these safeguards requires international cooperation, robust regulatory frameworks, and continuous technological innovation to address emerging threats. The IAEA has initiated the development of specialized measures for SMRs, potentially including enhanced monitoring and the embodiment of safeguards considerations into the design of these reactors that take into account the unique characteristics of these reactors.[9]

Economic considerations also play a role in the proliferation resistance of SMRs. The cost-effectiveness of SMRs, driven by their modular design and shorter construction times, can make them an attractive option for many countries. However, economic viability should not compromise security measures. Policies must ensure that cost reductions do not lead to decreased security and safeguard standards. The potential for widespread deployment of SMRs, with estimates suggesting the installation of approximately 1,000 small reactors by 2035,[10] necessitates a comprehensive approach to proliferation resistance addressing the more elements in the reactor operation (e.g., fuel, personnel, etc.) that balances economic, technical, and security considerations.

Considering the complicated nature mentioned above, while SMRs could offer significant advantages in terms of safety, flexibility, and economic viability, their proliferation resistance must be carefully managed. Advanced designs, robust international safeguards, effective regulatory frameworks, and comprehensive cybersecurity measures are essential to ensure that the benefits of SMRs do not come at the expense of increased proliferation risks. In case the arrival of the mass commercialization of the SMRs is inevitable, by addressing these challenges, the international community can harness the potential of SMRs to provide sustainable and secure energy solutions while mitigating the risks associated with nuclear proliferation.

B. High-Temperature Gas-cooled Reactors

High-Temperature Gas-Cooled Reactors (HTGRs) have garnered attention due to their advanced safety features, high efficiency, and potential for hydrogen production. The proliferation resistance of HTGRs is a crucial aspect of their deployment, particularly in the context of international nuclear non-proliferation efforts. This section evaluates the proliferation resistance of HTGRs, focusing on their design features, fuel cycles, and inherent security measures.

HTGRs utilize helium as a coolant, which is chemically inert and does not become radioactive. This choice of coolant enhances safety and reduces the risk of chemical reactions that could complicate proliferation resistance.[11] The core of HTGRs is typically designed with either prismatic blocks or pebble beds, both incorporating TRISO (tristructural-isotropic) fuel particles. TRISO fuel particles are highly robust, with multiple layers of ceramic materials that contain fission products and prevent the release of radioactive materials even at high temperatures. This robust fuel design is a significant barrier to proliferation, as it complicates the extraction of fissile material for weaponization. The high burn-up rates of HTGR fuel also contribute to proliferation resistance. Fuel burn-up rates in HTGRs can exceed 80 GWd/MT, producing highly radioactive spent fuel with poor isotopic quality for weapon use. The high burn-up not only maximizes energy extraction from the fuel but also results in spent fuel that is difficult to reprocess for weapons-grade material due to its high radiation levels and the presence of undesirable plutonium isotopes like Pu-240 and Pu-238. These isotopes complicate the use of separated plutonium in nuclear weapons, adding an additional layer of proliferation resistance (although even those poor-grade plutonium could be used to manufacture nuclear explosives with advanced design). Moreover, the physical and chemical characteristics of TRISO fuel make reprocessing challenging. The TRISO particles are encased in graphite, and separating the fissile material requires complex chemical processes such as grind-leach or burn-leach methods. These processes are technically demanding and require significant infrastructure, which acts as a deterrent to proliferation. The TRISO fuel's design inherently resists chemical attacks, reducing the risk of illicit reprocessing.

In terms of physical security, HTGRs benefit from their high-temperature operation and passive safety features. The reactors are designed to handle loss-of-coolant accidents without the risk of a core meltdown, as the core can dissipate heat through natural convection and radiation. This passive safety reduces the attractiveness of HTGRs as targets for sabotage or terrorism. Additionally, many HTGR designs incorporate below-grade reactor vessels, which provide natural protection against physical attacks and enhance security against unauthorized access as the pressure vessels are utilizing the cooling pool and earth as barriers. The deployment of HTGRs also involves stringent safeguards and monitoring measures. These measures include visual tracking of fuel elements, bulk accountability methods, and active neutron interrogation techniques to ensure the integrity and proper use of nuclear materials.

However, there are still proliferation risks associated with HTGRs. Like many commercialized reactors, the export of HTGR technology necessitates the transfer of technical expertise, which could be misused in a clandestine production reactor. The technical knowledge required to operate and maintain HTGRs could potentially be exploited to develop nuclear weapons capabilities from a human resource perspective, particularly if a state has access to natural uranium and other essential materials.

Thus, HTGRs offer several advantages in terms of proliferation resistance, including robust fuel design, high burn-up rates, and stringent safety and security measures. These features make it difficult to divert fissile material for weaponization and ensure that HTGR technology can be deployed safely and securely in the global effort to promote sustainable and non-proliferative nuclear energy. However, the transfer of technical expertise and the potential for clandestine operations remain concerns that must be addressed through rigorous international safeguards and oversight.

C. Advanced Nuclear Fuel Cycles including High-Assay Low-Enriched Uranium

Given the historical concerns over the diversion of nuclear materials for weapons production, the proliferation resistance of advanced-reactor-associated fuel cycle (also referred to as advanced fuel cycle in this article) technologies is particularly crucial. This section examines the inherent proliferation resistance features and the challenges of the advanced fuel cycle, explicitly focusing on the advanced closed fuel cycle for advanced reactors and the concerns raised with High-Assay Low-Enriched Uranium.

The advanced closed fuel cycle employed with advanced reactors involves the repeated recycling of nuclear fuel in fast reactors, which can significantly extend the availability of nuclear power and reduce nuclear waste. One of the key components of this cycle is the use of fast reactors that can burn long-lived actinides, including plutonium, from used nuclear fuel, thus minimizing the long-term radiotoxicity and volume of nuclear waste. The recycling process also incorporates innovative separation techniques such as the GANEX (grouped actinide extraction) process,[12] which enhances proliferation resistance by extracting uranium, plutonium, and minor actinides together, thereby avoiding the production of pure plutonium streams that are more susceptible to military diversion. These advanced techniques create substantial material and radiological barriers, complicating potential proliferation efforts. Additionally, the TOPS (Technological Opportunities To Increase The Proliferation Resistance Of Global Civilian Nuclear Power Systems)[13] and PR&PP (Proliferation Resistance and Physical Protection) methodologies assess various barriers to proliferation, ensuring robust technical, material, and institutional safeguards as they increase the difficulty of proliferation. These assessments highlight the enhanced security offered by advanced reactor systems through difficult-to-divert isotopic compositions and advanced monitoring technologies.

However, despite these advancements, the advanced fuel cycle presents challenges to non-proliferation efforts. The increased complexity and technological sophistication required for advanced reactors also mean that a higher level of technical expertise is necessary for their operation and oversight, potentially widening the proliferation risk if knowledge highly valuable for weaponization (i.e., reprocessing and plutonium separation) is misused. The need for advanced safeguards and continuous monitoring to manage the increased nuclear material flows also poses logistical and financial challenges.[14] Moreover, the initial stages of fast reactor deployment might still require pure plutonium, raising immediate proliferation concerns until more proliferation-resistant cycles like GANEX become fully operational. While actinides can be consumed during the operation of the fast reactor designs, the question of whether the sealing of core can be secured and immune to external extraction attempts throughout the entire reactor life is raised to the policymaker, especially when ensuring international cooperation and compliance with stringent safeguards, particularly in countries new to nuclear technology, still remains a critical challenge. The introduction of High-Assay Low-Enriched Uranium then aggravated these unsolved concerns.

Although it is not necessarily for the advanced reactor-associated fuel cycle, high-assay low-enriched uranium (HALEU) is an emerging fuel type gaining attention due to its potential to enhance the efficiency and performance of advanced nuclear reactors. HALEU is uranium that has been enriched to a higher concentration of the fissile isotope U-235 than the standard low-enriched uranium but less than 20%, typically between 5% and 19.75%. This enrichment level provides significant advantages in terms of reactor performance, fuel cycle flexibility, and waste management while also posing unique challenges and considerations for proliferation resistance.

HALEU fuels are particularly advantageous for advanced reactor designs, including SMRs and HTGRs, due to their higher energy density and improved neutron economy. These characteristics enable more compact core designs, longer operational cycles between refueling, and potentially lower overall fuel costs. However, the higher enrichment levels also require stringent measures to prevent the diversion of nuclear materials and ensure that HALEU is used exclusively for peaceful purposes.

The proliferation resistance of HALEU is multifaceted, involving technical, regulatory, and operational aspects. From a technical standpoint, the enrichment level of HALEU, while below the threshold for HEU, is sufficiently high to warrant increased security measures.[15] The use of HALEU in nuclear reactors necessitates robust safeguards to prevent its diversion for weapons production. According to a study on the weapons potential of HALEU, even at enrichment levels below 20%, there is a theoretical risk of its use in improvised nuclear devices if sufficient quantities are acquired and further enriched. Comprehensive physical protection and material control measures are essential to mitigate these risks. This includes stringent accounting and surveillance protocols to track the movement and usage of HALEU throughout its lifecycle, from enrichment and fuel fabrication to reactor operation and eventual disposal.

In addition to physical security measures, the proliferation resistance of HALEU can be bolstered through advanced fuel design and reactor technology. For instance, integrating HALEU into TRISO fuel particles, as used in HTGRs, adds layer of security. The robust TRISO coating encapsulates the uranium, making it difficult to access and reprocess without sophisticated technology. This inherent barrier complicates efforts to extract fissile material for weaponization, thereby enhancing the proliferation resistance of HALEU-based fuels. The economic and logistical considerations of HALEU also play a role in its proliferation resistance as the production and transport of HALEU are more complex and costly than standard LEU, thus offering higher traceability in a legal market. The need for specialized infrastructure to handle and process HALEU adds to the barriers against its proliferation and is a precursor for the international community to identify the actor seeking reprocessing capacity. Furthermore, international cooperation and agreements on the supply and use of HALEU can reinforce these barriers, ensuring that HALEU is accessible only to countries and entities committed to non-proliferation.

However, the proliferation risks associated with HALEU cannot be eliminated. Compared to LEU, the relatively higher enrichment levels mean that HALEU must be handled carefully to prevent its misuse. Continuous improvements in safeguard technologies, such as real-time monitoring systems and advanced detection methods, are necessary to stay ahead of potential proliferation threats. Additionally, international policies must evolve to address the specific challenges posed by HALEU, including clear guidelines for its production, transport, and use.

III. Impact of Advanced Nuclear Technologies on Non-Proliferation

A. Impact on Non-Proliferation Efforts

Advanced nuclear technologies, specifically advanced reactors, present both opportunities and challenges for non-proliferation efforts. These technologies are engineered with features aimed at reducing the risk of nuclear proliferation, yet the effort might be highly limited due to other design criteria. By integrating processes like the GANEX, advanced reactors can extract uranium, plutonium, and minor actinides together, avoiding the creation of high-grade plutonium suitable for military diversion. However, whether these evolving technologies are worth installing in terms of the proliferation resistance when compared to a once-though fuel cycle is still pending further studies involving economics, reliability, and many other considerations, this research considers these technologies passive resorts when facing weaponization.

Moreover, the PR&PP methodology and the TOPS assessments provide frameworks for ensuring that these advanced systems have robust safeguards. These methodologies highlight the technical, material, and institutional barriers necessary to prevent the misuse of nuclear materials. Enhanced monitoring technologies and difficult-to-divert isotopic compositions further support the non-proliferation objectives by making unauthorized use of nuclear materials more detectable and difficult.

However, the complexity and sophistication of advanced reactor technologies introduce new challenges. The advanced nature of these systems requires significant technical expertise and infrastructure, which may not be readily available in all regions. This necessity could lead to increased dependence on international support, raising concerns about the spread of sensitive knowledge. Additionally, the initial deployment stages of these reactors might still necessitate the handling of substantial quantities of fissile materials, posing immediate proliferation risks. Effective international cooperation, stringent regulatory frameworks, and continuous innovation are critical to address these risks and support non-proliferation goals.

B. Influence on DPRK's Energy Market

The introduction of advanced nuclear technologies into the DPRK could profoundly impact its energy market and economic landscape. The DPRK has long struggled with severe energy shortages and economic challenges, exacerbated by international sanctions. SMRs and HTGRs offer potential solutions by providing reliable, efficient, and scalable energy sources. These technologies could significantly alleviate energy shortages, enhance economic stability, and improve the quality of life for the DPRK population, for which Kim's regime possesses different degrees of need.

The promise of accessing advanced nuclear technologies could also serve as a strategic incentive for the DPRK to engage in denuclearization talks. The international community could leverage the prospect of economic development and technological cooperation to encourage the DPRK to dismantle its nuclear weapons program. Historical precedents, such as the Agreed Framework of 1994 and the Six-Party Talks, demonstrated that linking economic incentives with denuclearization efforts could be effective. However, the successful implementation of such an approach requires overcoming significant challenges. China and Russia, as key players in the nuclear technology market while considering their continuous historic friendship with DPRK, offer distinct options that could support the DPRK's nuclear energy ambitions while addressing non-proliferation concerns. China is advancing with advanced reactors like the ACP100[16] and HTR-PM.[17] The ACP100, a small modular reactor, offers scalability and enhanced safety features, making it ideal for the DPRK's incremental energy needs. The High-Temperature Gas-Cooled Reactor Pebble-bed-Module (HTR-PM) went even further by combining the concepts of SMR and HTGR, which offered another viable option under sufficient safeguard measures. Meanwhile, Russia's approach emphasizes strategic partnerships and comprehensive support, including fuel supply and waste management,[18] which could provide the DPRK with the necessary infrastructure and technical support to maintain safe and secure nuclear operations while maintaining a possible degree of first-line surveillance on military diversion. Though the openness of the nuclear energy market and industries are still heavily limited in China and Russia, such arrangements did at least offer an additional portal to introduce the impact on DPRK from the rest of the world.

The DPRK's political and economic isolation, combined with stringent international sanctions, presents substantial obstacles to the importation and deployment of advanced nuclear technologies. Ensuring that these technologies are used solely for peaceful purposes demands robust international oversight and stringent safeguards. The risk of proliferation remains a critical concern even when such cooperation is viable, as the knowledge and infrastructure necessary for peaceful nuclear energy can also be diverted for weaponization. Addressing these challenges necessitates a comprehensive strategy that includes diplomatic engagement, economic incentives, and rigorous monitoring by international bodies.

C. Strategic Considerations for DPRK

Deploying advanced nuclear technologies in the DPRK involves significant strategic considerations, particularly concerning the nation’s military and security posture. Advanced reactors and their associated fuel cycle technologies could potentially shift the DPRK’s defense strategy by offering an alternative means of achieving energy security without the need for nuclear weapons. These technologies align with international non-proliferation norms and could reduce the DPRK’s perceived need for nuclear armament as leverage for international aid.

Nevertheless, the transition to these advanced technologies is fraught with risks. The DPRK’s current lack of technical expertise and infrastructure for operating and maintaining advanced reactors could lead to increased dependence on international support and oversight, potentially undermining national sovereignty. The likely scenario would also weaken DPRK’s will to pursue negotiation with the outer world. Again, the dual-use nature of nuclear technology poses an inherent risk, as the skills and infrastructure developed for civilian applications could be diverted to military purposes if not adequately controlled. However, this case also implies that with proper guidance and management, civilian nuclear development could provide a good opportunity to convert the military workforce to peaceful purposes. Ensuring robust security measures, comprehensive safeguards, and international cooperation is essential to mitigate these risks and build regional and global trust.

IV. Implementation Strategies for Advanced Nuclear Technologies

A. Addressing DPRK's Energy Gap

While DPRK faces severe energy shortages, which are exacerbated by its political isolation and outdated infrastructure, the intention of continuing the economic boost from the Ukraine conflict could play a key role in motivating DPRK's leader to come back to the negotiation regarding denuclearization. Advanced nuclear reactor technologies could offer potential solutions to bridge the energy gap while some of their intrinsic features grant fewer concerns for their providers to export. SMRs, with their smaller size and modular design, are particularly suitable for the DPRK. They can be deployed incrementally to match the specific energy demands and can be fabricated in factories, which reduces on-site construction time and costs while reducing the burden of its on-site safeguard. HTGRs, known for their high efficiency and safety features, provide another viable option if the DPRK intends to have a more advanced reactor design.

However, deploying these technologies in the DPRK presents significant technical, economic, and logistical challenges. The country's existing infrastructure may not support the advanced requirements of SMRs and HTGRs without substantial upgrades. Moreover, the political and economic isolation of the DPRK, combined with stringent international sanctions, poses barriers to importing the necessary technology and expertise. Despite these challenges, the long-term benefits of adopting advanced nuclear technologies could be substantial. These reactors can provide a reliable and continuous power supply, which is crucial for the DPRK's economic development and stability, and also constitute a leverage preventing the DPRK from easily withdrawing from the conversation.

The adoption of advanced nuclear reactors, along with other non-carbon technologies such as renewable energy technologies, could provide attractive options for long-term sustainability and economic benefits for the DPRK. The long-term benefits provided by such energy programs also foster a more sustainable momentum in maintaining the negotiation while potentially building the DPRK's dependence and trust on the outside world. Additionally, technologies and devices offered by the Chinese or Russian providers are more acceptable to DPRK's leadership for geopolitical reasons. China and Russia's engagement in related fields is unlikely to damage but likely provoke the competitiveness of other countries' nuclear industries, considering they are unlikely to get involved in the first place. Instead, it could open a window on DPRK's energy market to the rest of the world by allowing them to invest or trade indirectly.

Economically, the deployment of advanced nuclear reactors could lead to cost savings in the long run. While the initial investment in technology and infrastructure is high, the modular nature of SMRs and the high efficiency of HTGRs can result in lower operational and maintenance costs, which result in less burden in diplomatic engagements. However, there are potential barriers to long-term implementation, such as the need for continuous technological upgrades, high maintenance costs, and the necessity for a skilled workforce to operate and maintain these reactors.

Diplomatic Initiatives for Energy Cooperation

International collaboration is essential to successfully implementing advanced nuclear technologies in the DPRK. Diplomatic initiatives should focus on fostering energy cooperation between the DPRK and countries with advanced nuclear capabilities. This collaboration could involve technology transfer, joint ventures in nuclear technology, and training programs to build local expertise. Overcoming diplomatic hurdles, such as mistrust and geopolitical tensions, is crucial. Engaging in multilateral dialogues and leveraging international organizations like the IAEA can help facilitate these initiatives.

Ensuring Reliable Energy Supply Through International Partnerships

Building robust international partnerships is key to ensuring a reliable energy supply for the DPRK. These partnerships should include agreements on the supply of nuclear fuel, technology transfer, and technical support. Establishing a framework for cooperation that includes safeguards and verification mechanisms can help maintain trust and transparency. Additionally, international partnerships can provide the DPRK with access to the latest advancements in nuclear technology, ensuring the sustainability and efficiency of its nuclear energy program.

B. Enhance Control over Reprocessing Technology and Facility

Reprocessing facilities may play a crucial role in managing spent nuclear fuel but increase proliferation risk substantially. Though from a critical control standpoint, spent fuel with higher reprocessing interest also took much longer in the reprocessing process, which may depreciate its covert weaponization value, their reprocessing facilities still present significant proliferation risks as the technologies and materials involved can be diverted for weaponization as plutonium gets separated. In the context of the DPRK, establishing a reprocessing facility could also raise strong concerns about the potential misuse of reprocessed materials for nuclear weapons production which, at a given stage, once-through fuel cycle is more sound, or at least, the facility capable of closing the cycle needs to be placed under international safeguards.

Advanced reprocessing technologies enhance proliferation resistance by avoiding the ideal weaponization condition for plutonium. However, the effort to implant technology may not completely offset the intrinsic proliferation risk from conducting reprocessing, especially with threats to international safeguards constantly involved. Implementing such technology in the DPRK would require significant international oversight to ensure that reprocessed materials are not diverted for non-peaceful purposes. Meanwhile, studies on advanced fuel designs preventing unauthorized reprocessing need to be integral to enhancing proliferation resistance, yet encountered a similar dilemma in which the technology is offering a solution, yet its implantation is very difficult to guarantee. High-assay Low-enriched Uranium fuels, for example, offer significant advantages in terms of reactor performance and waste management while posing unique challenges for proliferation resistance due to their weaponizable nature. Integrating HALEU into TRISO fuel particles, as used in High-Temperature Gas-cooled Reactors, adds an additional layer of security. The robust TRISO coating encapsulates the uranium, making it difficult to access and reprocess without sophisticated technology, thus enhancing the proliferation resistance of HALEU-based fuels.

Framework for Enhancing Reprocessing Safeguard

A robust framework for enhancing safeguards is essential to effectively reduce proliferation risks associated with reprocessing if reprocessing is necessary. This includes implementing stringent accounting and surveillance protocols to track the movement and usage of nuclear materials throughout their lifecycle. International cooperation is crucial and may involve multilateral interlock agreements between reactor providers, fuel producers, and reprocessing facilities (for example, no country could hold more than one role in DPRK's energy program) to ensure effective safeguards during the device and technology transfer. Such arrangements ensure transparency and accountability, reducing the risk of unauthorized reprocessing.

Enhanced Initiatives for Research Increasing Proliferation Resistance on Reprocessing

Further research is needed to increase the proliferation resistance of reprocessing technologies. This includes developing advanced fuel designs that incorporate physical protection measures and feasibility studies on pre-installed impurities to prevent unauthorized reprocessing. Additionally, research on safeguard surveillance technologies, such as real-time monitoring systems and advanced detection methods, is necessary to stay ahead of potential proliferation threats. International policies must evolve to address the specific challenges posed by advanced reprocessing technologies, ensuring that they are used exclusively for peaceful purposes.

C. Transferring DPRK from a Nuclear State to a Latency State

Considering the recent geopolitical development on the Korean Peninsula, especially the

DPRK's constitutional amendment in 2023[19] and Kim's new declaration on the North-South Korean relationship in 2024,[20] a simple and direct denuclearization, or even a vague promise of it seems to be inapproachable. However, though he bluntly described DPRK as a "nuclear-armed nation" in his speech to the Supreme People's Assembly, Kim also defined the status as an "already started arduous journey." The later released statement from the Ministry of Foreign Affairs[21] also indicated the political significance of the self-proclaimed "Nuclear Weapon State" status. These indications would require policymakers to explore a sophisticated solution tailored to DPRK's desire, or at least the need for propaganda. A de facto denuclearization process with a de jure state with nuclear latency would hold much higher practicality over DPRK revoking its claim. Transferring the DPRK from a nuclear-weapon-holding state to a nuclear-latency state involves a systematic and phased approach aimed at reducing the country's nuclear capabilities while ensuring incremental compliance with international non-proliferation norms. A nuclear latency state is one in which a country possesses the technological capability to develop nuclear weapons but chooses not to do so, maintaining a peaceful nuclear program under strict international oversight, where detailed scrutiny regarding enrichment and reprocessing capacity is essential to ensure a successful downgrading process so peaceful intention can be verified. This transition requires the DPRK to dismantle its existing nuclear weapons (at least partially at the beginning), cease further development of such weapons, and subject its nuclear facilities to comprehensive international inspections and safeguards. Considering the need for DPRK's leadership to prolong its economic growth, two tracks, disarmament and civilian transition, need to be progressed simultaneously.

Transition Strategy to Nuclear Latency

The first track in the latency transition involves establishing a verifiable framework for the dismantlement of the DPRK's nuclear weapons program. This includes the deactivation and dismantlement of nuclear warheads, the decommissioning of production facilities, and the safe disposal of fissile materials. International bodies such as the IAEA would play a crucial role in verifying these activities, ensuring transparency, and building trust among global stakeholders.

Meanwhile, the DPRK would need to transition its nuclear infrastructure towards exclusively civilian purposes. This involves re-purposing existing facilities for energy production, medical applications, and industrial uses. Advanced nuclear technologies can support this transition by providing robust energy solutions with a stable market that is inherently designed with proliferation resistance to alleviate the concern of remilitarization. These technologies, combined with stringent international safeguards, can help ensure that nuclear materials are not diverted for military use. Additionally, training and capacity-building programs for DPRK scientists and technicians will be essential to facilitate the shift toward a peaceful nuclear program.

The Joint Comprehensive Plan of Action (JCPOA)[22] with Iran serves as a relevant model for transitioning North Korea toward denuclearization. The JCPOA's framework incorporates stringent verification measures, phased sanctions relief, and regular inspections, which could be adapted to address the unique challenges posed by the DPRK's nuclear program through incremental measures. The phased relief of economic sanctions, linked to verifiable milestones in denuclearization, would incentivize compliance while alleviating DPRK's economic isolation. Key to this model is the involvement of the International Atomic Energy Agency (IAEA) in implementing a comprehensive monitoring regime. For the DPRK, this would entail agreeing to extensive oversight, including real-time surveillance of nuclear facilities, detailed accounting for all nuclear materials, and the application of rigorous safeguards to ensure compliance. These measures are essential for transparency and building international trust. While the JCPOA's success in temporarily containing Iran's nuclear ambitions offers valuable lessons, the DPRK's distinct strategic calculus demands a bespoke approach that prioritizes robust verification, sustained diplomacy, and a credible mix of incentives and enforcement.

Benefits and Challenges of Nuclear Latency

Transitioning the DPRK to a nuclear latency state offers several strategic benefits. First, it reduces the immediate threat of nuclear proliferation and potential conflict in the region, enhancing regional and global security. Second, it opens up avenues for economic and technological cooperation with the international community, providing the DPRK with access to advanced nuclear technologies for peaceful purposes. This can lead to improvements in energy security, healthcare, and industrial development within the country, contributing to its overall economic stability and growth.

However, the transition to a nuclear latency state is fraught with challenges. One of the primary obstacles is the DPRK's potential resistance to giving up its nuclear arsenal, which it views as a critical component of its national security and bargaining power. Ensuring the credibility and reliability of security assurances from the international community will be crucial in addressing these concerns. Additionally, the technical and logistical challenges of dismantling nuclear facilities, managing nuclear waste, and re-purposing infrastructure require substantial resources and expertise.

Furthermore, maintaining a nuclear latency state involves continuous monitoring and verification to prevent any covert development of nuclear weapons. This necessitates robust international cooperation, advanced surveillance technologies, and stringent regulatory frameworks. Diplomatic efforts must also focus on building and maintaining trust between the

DPRK and the international community, ensuring that economic incentives and security guarantees are credible and sufficient to deter any attempts at nuclear rearmament.

V. Conclusion

The Democratic People's Republic of Korea continues to present a significant challenge to global non-proliferation efforts. Its persistent advancement of nuclear weapons capabilities underscores the limitations of previous diplomatic strategies and the complexity of achieving meaningful denuclearization. Recent advancements in nuclear reactor technologies, including Small Modular Reactors(SMRs), High-Temperature Gas-cooled Reactors(HTGRs), and advanced nuclear fuel cycles, offer potential new avenues for addressing this issue. However, these technologies are not without their challenges and risks, necessitating a cautious and critical evaluation.

SMRs and HTGRs are promising in their ability to provide energy solutions tailored to the DPRK's needs. With modular designs and enhanced safety features, SMRs allow for incremental deployment and controlled scalability. Similarly, HTGRs' robust safety profiles and fuel designs could reduce the likelihood of material diversion. These attributes present a theoretical framework for mitigating the proliferation and security risks associated with nuclear energy. High-Assay Low-Enriched Uranium (HALEU), a key component of advanced fuel cycles, further enhances fuel efficiency and performance. However, its higher enrichment levels also pose a proliferation concern, as its reprocessing or direct access could theoretically yield weaponizable material.

Reprocessing represents a critical area of concern in this context. The potential for extracting plutonium from spent nuclear fuel, particularly from reactors employing advanced fuel cycles, significantly complicates non-proliferation efforts. While advanced reprocessing technologies aim to make plutonium separation more difficult or less attractive, they cannot entirely eliminate the associated risks. In a scenario like the DPRK's, where transparency and trust are minimal, the establishment of reprocessing facilities could be misused for clandestine weapons programs. Even with stringent safeguards, the dual-use nature of these technologies necessitates robust international oversight, which might prove difficult to achieve in the DPRK's highly insular and militarized governance structure.

The dual-use risk extends to technical expertise and infrastructure. Technologies such as SMRs and HTGRs demand sophisticated operational knowledge and infrastructure, which could be repurposed for non-peaceful applications. Moreover, advanced reactors with long-lived cores, although reducing the frequency of refueling, may accumulate significant quantities of plutonium, increasing proliferation risks if adequate safeguards are not enforced, as reprocessing is not excluded from the current possibilities. The risk of cyber-attacks further complicates the safe deployment of these reactors, as unauthorized access to digital controls could compromise material security or reactor functionality.

While these technologies undoubtedly expand the toolkit for addressing proliferation concerns, their application in the DPRK must be approached with caution. Introducing advanced reactors or fuel cycles without addressing the broader geopolitical and security dynamics could inadvertently exacerbate the risks of proliferation. Effective international frameworks, coupled with rigorous verification mechanisms, are essential to prevent the misuse of these technologies.

In conclusion, while advanced nuclear technologies provide new options for mitigating proliferation risks and addressing energy deficits, their deployment is fraught with challenges. The risks associated with reprocessing, material diversion, and technical knowledge transfer cannot be ignored. These technologies should not be viewed as standalone solutions but rather as components of a comprehensive strategy that integrates technical innovation with robust international oversight, diplomatic engagement, and economic incentives. A cautious, incremental approach, grounded in transparency and global cooperation, is critical to ensuring these tools contribute positively to denuclearization efforts.

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Author Profiles

Anthony Dai

Anthony Dai is currently a Graduate Research Assistant at the James Martin Center for Nonproliferation Studies. He also served as a Research Fellow at the Comprehensive Nuclear-Test-Ban Treaty Organization and a Freeman Foundation Awardee at the Research Center for Nuclear Weapons Abolition, Nagasaki University. He holds an M.S. from UC Berkeley and a B.S. from Rensselaer Polytechnic Institute, both in nuclear engineering. As a Keepin Fellow, Anthony received advanced training in safeguard inspection at Los Alamos National Laboratory. His research interest channeled technical expertise to treaty verification and disarmament policy, empowered by his native Chinese language capacity.

Research Center for Nuclear Weapons Abolition, Nagasaki University(RECNA)
長崎大学核兵器廃絶研究センター（RECNA）

1-14 Bunkyo-machi, Nagasaki, 852-8521, Japan
〒852–8521 長崎市文教町1－14

TEL. +81 95 819 2164 ／ FAX. +81 95 819 2165
[E-mail] recna_staff@ml.nagasaki-u.ac.jp
http://www.recna.nagasaki-u.ac.jp