Technical Paper
https://doi.org/10.7733/jnfcwt.2023.029

An Analysis of Constraints on Pyroprocessing Technology Development in ROK Under the US Nonproliferation Policy

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(Received June 24, 2023 / Revised July 5, 2023 / Approved July 10, 2023)

Since 1997, the Republic of Korea (ROK) has been developing pyro-processing (Pyro) technology to reduce the disposal burden of high-level radioactive waste by recycling spent nuclear fuel (SNF). Compared to plutonium and uranium extraction process, Korean Pyro technology has relatively excellent proliferation resistance that cannot separate pure plutonium owing to its intrinsic characteristics. Regarding Pyro technology development of ROK, the Bush administration considered that Pyro is not reprocessing under the Global Nuclear Energy Partnership, whereas the Obama administration considered that Pyro is subject to reprocessing. However, the Bush and Obama administrations did not allow ROK to conduct full Pyro activities using SNF, even though ROK had faithfully complied with international nonproliferation obligations. This is because the US nuclear nonproliferation policy to prevent the spread of sensitive technologies, such as enrichment and reprocessing, has a strong effect on ROK, unlike Japan, on a bilateral level beyond the NPT regime for non-proliferation of nuclear weapons.

Keywords: Pyroprocessing, Nuclear, Nonproliferation, Reprocessing, GNEP, Nuclear cooperation agreement

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1. Introduction

In May 2022, the Yoon administration, in the national agenda including 110 issues, announced a policy to expand the use of nuclear power plants (NPPs), discarding the nuclear phase-out policy of the Moon administration and restoring supply chain capabilities of the Korean nuclear industry. Expanding the use of NPPs as a carbon-free power source can contribute to achieving the 2030 Nationally Determined Contribution of the Republic of Korea (ROK), as well as strengthening energy security by reducing ROK's dependency on foreign energy imports [1]. However, since the expanded use of NPPs inevitably leads to an increase in the amount of spent nuclear fuel (SNF), ROK needs to secure various options of SNF management, including direct disposal, to continue using nuclear energy as a sustainable energy source.

Since 1997, the Korean government has been developing pyro-processing (Pyro) technology, as a dry processing that can reduce the disposal burden of high-level radioactive waste (HLW) by recycling SNF. In particular, in December 2008, the Korean government established the mid- to long-term research and development (R&D) plan including domestic demonstration of Pyro-Sodium cooled Fast Reactor (SFR) linkage. In addition, since 2011, ROK in collaboration with the United States has been conducting the Joint Studies (JS) to verify the feasibility of technical feasibility, economic viability, and non-proliferation acceptability of Pyro.

However, controversies over Pyro R&D of ROK have emerged in the United States since the mid -2000s. These controversies were largely raised in the process of launching the Global Nuclear Energy Partnership (GNEP) and JS, and negotiating the revision of ROK-U.S. Nuclear Cooperation Agreement (ROK-US NCA) under nuclear non-proliferation policies of the Bush and Obama administrations.

This paper addresses the feasibility of Pyro technology that ROK is developing for the peaceful use of sustainable nuclear energy. Based on this, it was described how the US nuclear non-proliferation policy has acted as constraints on ROK in the process of conducting Pyro R&D.

2. Feasibility of Pyroprocessing R&D in ROK

2.1 Necessity of Spent Fuel Management Option

As of April 2023, ROK is operating 25 NPPs, ranking fifth in the world in terms of installed capacity [2]. In May 2022, the Yoon administration announced a policy to expand the use of NPPs, discarding the nuclear phase-out policy of the Moon administration and strengthening the supply chain of Korean nuclear industry [3]. In this regard, the Ministry of Trade, Industry and Energy established the plan of the 10th Electricity Supply and Demand in January 2023 [4]. According to this plan, the installed capacity of NPPs is expected to be increased from 24.7 GW in 2022 to 31.7 GW in 2036 with the operation of 10 NPPs and the new construction of two NPPs (Shinhanul Units 3 and 4). In December 2022, with reference to the EU green taxonomy, the Ministry of Environment added economic activities of NPPs to the Korean green taxonomy which has reduction of greenhouse gas emission, adaptation of climate change, sustainable conservation of water, transition to circular economy, prevention and management of pollution, and conservation of biodiversity as core goals, under the condition of early securing a HLW disposal site and using accident-tolerant fuel in 2031 [5].

The policy of the Yoon administration to expand the use of nuclear energy as a carbon-free power source will contribute to the ROK's greenhouse gas reduction target, which has been raised to respond to climate change. In addition, this policy recognizes the importance of nuclear energy as a technology-intensive, quasi-domestic energy with excellent economic feasibility compared to other power sources in a situation where the importance of energy security increases after the Russian invasion of Ukraine [6].

However, SNF is inevitably generated in accordance with the use of NPPs. In ROK, approximately 18,300 tons of SNF was generated as of the end of September 2022 [7]. If the 10th electricity supply and demand plan of the Yoon administration is carried out, more than 38,400 tons of SNF is expected to be generated. In order for ROK to continue to use sustainable nuclear energy, it is necessary to develop management options for SNF, including securing a HLW disposal site. However, the Korean government has not yet secured a HLW repository. In this regard, mass media has criticized the construction of new NPPs as that of apartments without toilets. In particular, in the process of selecting a site for HLW disposal in the past, objections in Guleop-do, Anmyeon-do, and Buan province prove how difficult it is to secure a HLW disposal site in ROK, which were conducted under the leadership of the government without any legal basis.

Accordingly, national assembly members introduced special bills for democratic selection of HLW disposal sites, support of local residents in the vicinity of the repository, the establishment of a radioactive waste management committee, and so on. The HLW repository is also necessary for the SNF management to be generated from the operation of future NPPs as well as generation from existing NPPs, regardless of whether NPPs are phased out or not. However, special bills aren't being passed due to political disputes between the Democratic Party, which is the position of nuclear phase-out of the Moon administration, and the People's Power Party, which is the expanded use of NPPs of the Yoon administration.

Regarding the SNF management, deep geological disposal (DGD) is widely recognized internationally as a safe management option for SNF. DGD is a method to prevent radioactive materials from reaching the human living sphere by placing SNF in a safe canister 300 to 1,000 meters underground [8]. In particular, based on the method developed by Sweden, Finland is expected to be able to operate a permanent repository for SNF in 2024 for the first time in the world [9].

Based on Sweden's DGD method, ROK has also developed direct disposal technology suitable for the domestic geological condition since 1997. In particular, from 2021, technology for safe disposal of SNF is being developed as a multi-agency national R&D project of the Ministry of Science and ICT, Ministry of Trade, Industry and Economy, and the Nuclear Safety and Security Commission. If approximately 36,500 tons of SNF is directly disposed of through DGD, it is expected that more than 6.0 km^2 of HLW disposal site will be needed [10]. In this regard, the Korean government has been developing Pyro technology that can reduce the footprint and management period of the HLW disposal, along with DGD technology development for direct disposal of SNF.

2.2 The Objective and Technical Feasibility of Pyroprocessing R&D in ROK

In accordance with the 1st Comprehensive Nuclear Promotion Plan in 1997, the Korean government has been developing Pyro technology that can reduce the footprint and management period of HLW disposal for future generations. SNF with a burnup of 45,000 $MWd \cdot tU^{-1}$ and cooling time for 10 years contains ~93% uranium, ~1.4% transuranic elements (plutonium, americium, curium, neptunium, etc.) and less than 6% fission products. Pyro is a technology that extracts uranium and other transuranic elements "together" from SNF through an electrochemical method in high-temperature (550−600°C) molten salt. Pyro technology, when linked with the SFR being developed by ROK, not only recycles SNF, but also reduces the volume and toxicity. Through this, it is possible to reduce the area and management period of HLW disposal. According to the Korea Atomic Energy Research Institute, when Pyro is coupled with the SFR, it is expected that the area of HLW can be reduced to 1/68, the volume to 1/50, and the management period to 1/1000 compared to the direct disposal of SNF, based on the theoretical calculations. In particular, uranium and other transuranic elements recovered

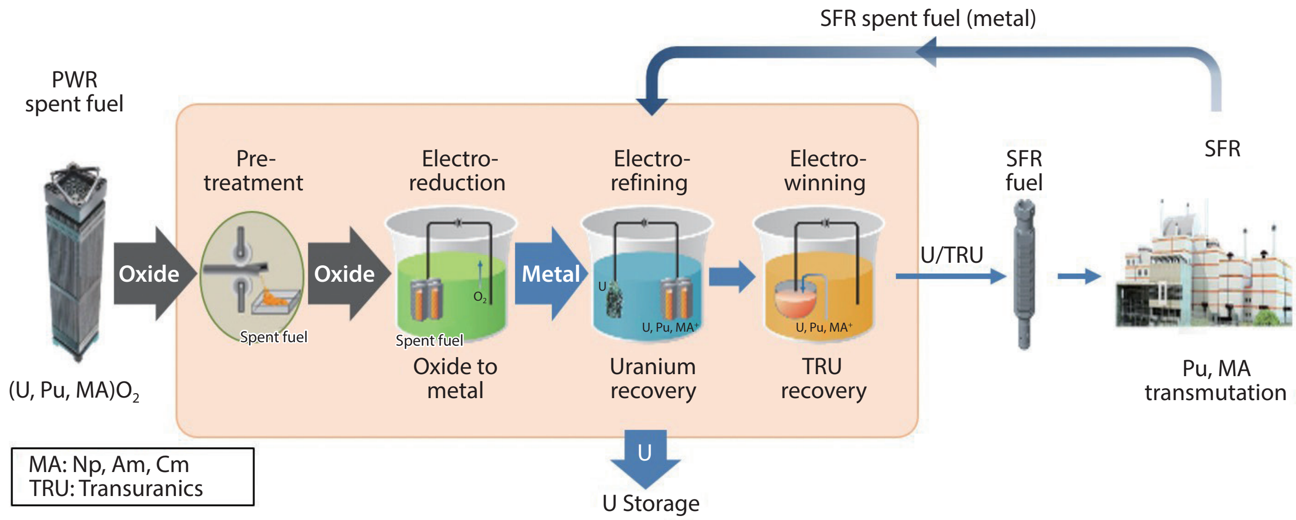

Fig. 1. Overview diagram of spent fuel recycling through Pyro-SFR linkage.

from SNF through Pyro technology can be used as fuel for electricity generation of SFR rather than as HLW. This can contribute to energy security as it is possible to supply fuel for advanced nuclear reactors domestically when Pyro technology is secured. An overview diagram of SNF recycling through Pyro-SFR linkage can be shown in Fig. 1.

In December 2008, the Korean Atomic Energy Commission established a mid- and long-term plan for future nuclear energy system development, and decided to develop Pyro-SFR technology including domestic demonstration [11]. In addition, the 10th Korean Atomic Energy Promotion Commission in December 2021 decided that the Pyro-SFR linkage system would have technical feasibility, safety and nonproliferation acceptability as a SNF management technology [12].

2.3 Evaluation of Nuclear Proliferation Sensitivity of Pyroprocessing

2.3.1 Definition and Scope of Reprocessing

'Reprocessing' can be divided into 're+processing' in English. If the word is etymologically interpreted, it could be processing something again. In other words, not only the activity of extracting pure plutonium from SNF, but also Post Irradiation Examination to analyze the integrity of SNF rod can be interpreted as reprocessing.

However, until now, in the international nuclear community, 'reprocessing' has referred to activities to extract pure plutonium and uranium from SNF. The International Atomic Energy Agency (IAEA) Safeguards Glossary defines a reprocessing plant as "a facility that chemically separates nuclear material from fission products following dissolution of spent fuel" [13]. The Nuclear Suppliers Group (NSG), which is leading the international nuclear export control system, also defines reprocessing in its export control guidelines as "separates plutonium and uranium from highly radioactive fission products and other transuranic elements" [14]. In addition, the US Congressional Research Service defines reprocessing as "chemically separating uranium and plutonium from irradiated nuclear fuel". These definitions view 'reprocessing' as a technology capable of extracting pure plutonium from SNF, such as plutonium and uranium extraction (PUREX), a wet processing method [15].

In particular, the United States, Russia, United Kingdom (UK), France, and China, which are the official nuclear weapon states (NWSs) under the treaty on the non-proliferation of nuclear weapons (NPT), developed plutonium-based nuclear weapons from the 1940s to the end of the 1960s by using the PUREX process, to obtain pure plutonium from SNF. In addition, all commercialized reprocessing facilities around the world, such as the La Hague reprocessing plant in France, the Sellafield reprocessing plant in the UK, and the Rokashomura reprocessing plant in Japan, use the PUREX process. No country in the world has conducted plutonium-based nuclear weapon development using Pyro technology yet. In this sense, it is reasonable to view 're-processing' as PUREX to extract pure plutonium, not Pyro.

2.3.2 Technical Characteristics of Pyroprocessing and Differentiation From Reprocessing

The nuclear proliferation sensitivity of SNF processing technology is determined by the purpose and nature of the technology. The largest category of SNF processing activities is alteration in form or content (Alteration) [16]. Alteration means an alteration in physical form or chemical content of nuclear material in SNF, no matter what technology is used [17].

Alteration that ROK attempted in the past or is currently performing, includes post-irradiation examination, direct use of PWR spent fuel in CANDU, Pyro, mixed oxide fuel manufacturing, tandem fuel cycle, and PUREX. Among Alteration activities, PUREX, which can extract pure plutonium, can be seen as having the highest nuclear proliferation sensitivity. In this reason, in the US Atomic Energy Act of 1954, as amended and Nuclear Non-Proliferation Act of 1978, the United States distinguishes between Alteration and reprocessing for strict control [16].

If a nuclear weapon is manufactured with mixed nuclear material other than pure plutonium from SNF, the performance of the nuclear weapon will not be good. ROK's Pyro technology cannot separate pure plutonium due to its electrochemical characteristics. As shown in Fig. 2, Pyro only can extract residual uranium and other transuranic elements together using a liquid cadmium cathode during the electrochemical process. A gap of the red-ox potential for separating plutonium is electrochemically very small, so that plutonium can be extracted together with these materials. Therefore, it is not appropriate for Pyro, which cannot separate pure plutonium, to be classified as reprocessing like PUREX.

In the case of direct disposal underground without processing SNF, the proliferation sensitivity is the lowest. PUREX, which can extract pure plutonium most easily, will have the highest proliferation sensitivity. In this case, there is an Alteration and reprocessing technology between 0 and 1. Fig. 3 shows the proliferation sensitivity of Alteration and reprocessing technologies. ROK's Pyro has lower proliferation sensitivity than PUREX, so it is reasonable to view it as Alteration category rather than reprocessing.

2.4 Compliance With Non-proliferation Obligations of ROK

As of June 2023, ROK has joined all international nuclear non-proliferation regimes for safeguards, export control and physical protection as nonproliferation measures under the NPT - NPT in April 1975, IAEA in August 1957 as a founding member and Additional Protocol in, Zangger Committee and NSG in October 1995, and the Convention on Physical Protection on Nuclear Material (CPPNM) in April 1982 - to ensure the peaceful use of nuclear energy.

As strengthened nuclear non-proliferation measures, ROK entered into force the Additional Protocol in February 2004 and the amendment to the CPPNM in May 2016. The IAEA board of governors made a broader conclusion in June 2008 that all nuclear material in ROK is being used peacefully.

As a non-nuclear weapon state (NNWS), ROK has taken steps to improve nuclear transparency on a voluntary basis. ROK government announced the 'Four Principles for the Peaceful Use of Nuclear Energy' to improve nuclear transparency regarding report failure of the IAEA safeguards in October 2004. In particular, ROK has made it clear to the international community that it will abide by the Joint Declaration on the Denuclearization of the Korean Peninsula (Joint Declaration) despite North Korea had conducted six nuclear tests. In addition, ROK introduced the world's first

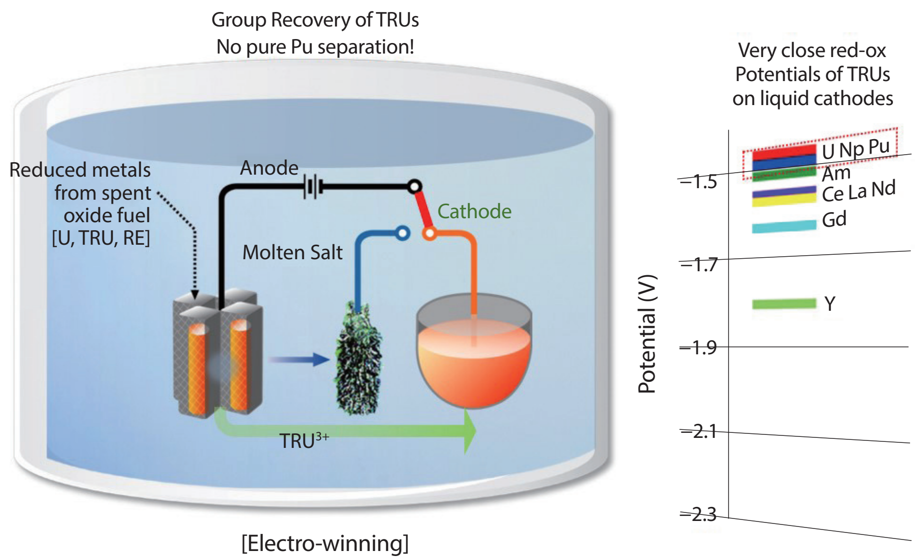

Fig. 2. Conceptual diagram of transuranic elements separation in the electro-winning process of Pyro.

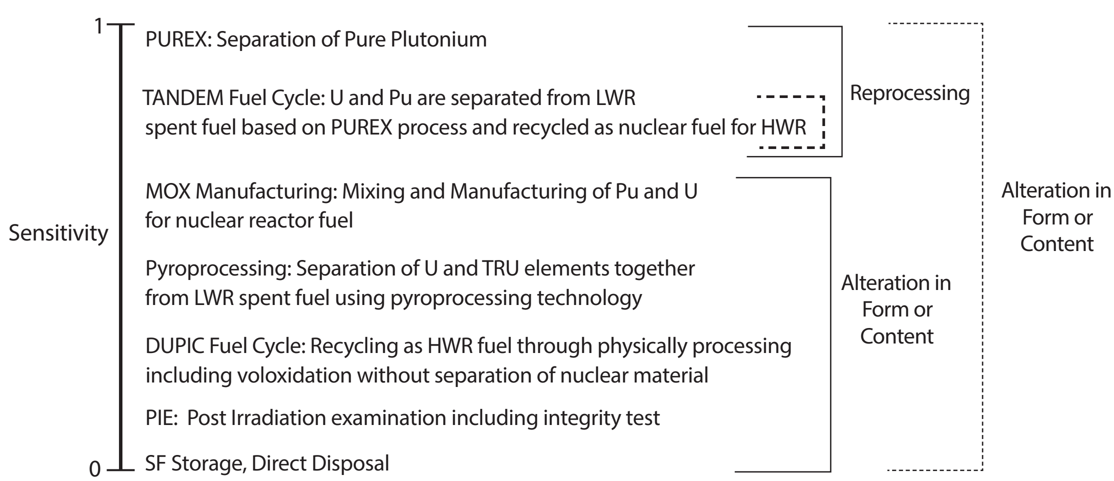

Fig. 3. Proliferation sensitivity of spent fuel processing technologies.

unannounced inspection of the IAEA in May 2016 [18]. ROK, along with the United States, is taking the lead in strengthening international nuclear security including hosting the 2nd Seoul Nuclear Security Summit in March 2012.

These nuclear non-proliferation efforts of ROK need to lead to the guarantee of peaceful use of nuclear energy in accordance with Article 4 of the NPT should be guaranteed. If faithful fulfillment of nuclear non-proliferation obligations is not guaranteed by peaceful uses of nuclear energy, the validity of nuclear non-proliferation obligations will be diminished.

3. Analysis of U.S. Nonproliferation Policy as Constraints of ROK's Pyro Technology Development

The United States conducted the first nuclear test in

July 1945 at Trinity, Nevada. Realizing the power of nuclear weapons, the United States has been leading international nuclear non-proliferation efforts since 1945 to the present to prevent the proliferation of nuclear weapons [19]. In this article, this section addresses the US policy change in the period from the early development of Pyro technology in 2001 to the negotiations on the revision of the ROK-US NCA until the mid-2010s, as the period when the controversy of ROK's Pyro technology development emerged the most in the US.

3.1 Cooperation and Restrictions on Pyro Under the Nonproliferation Policy of the Bush Administration

The goal of the non-proliferation policy of the George W. Bush administration, which was launched in January 2001, was to prevent the proliferation of sensitive technologies such as enrichment and reprocessing (ENR) that could produce highly enriched uranium and pure plutonium that can be directly used for nuclear weapons [19]. The Bush administration has become more aware of the need to strengthen the prevention of proliferation of sensitive technologies in relation to Iran's clandestine acquisition of ENR capabilities despite being a party to the NPT [20]. In addition, the Bush administration was concerned about a loophole in the NPT that allowed NPT parties to acquire ENR technologies and withdraw from the NPT under article 10 of the NPT [21]. In response, President Bush, in his speech at the National Defense University on February 11, 2004, guaranteed the supply of nuclear fuel to countries that had abandoned ENR, and suggested that NSG not supply ENR items [22].

However, on May 17, 2001, President Bush recognized the need to support recycling or reprocessing R&D of SNF to expand the use of nuclear energy in the United States, and this was well reflected in the White House's 'National Energy Policy' report published in May 2001 [23]. According to this report, the United States would allow research, development and deployment of fuel conditioning methods such as Pyro that can reduce volume of HLW radioactive waste and enhance proliferation resistance, and international cooperation in the field of advanced nuclear fuel cycle.

The policy change of the Bush administration, which does not view Pyro as a reprocessing, had important implications for ROK's Pyro technology development. The Bush administration started cooperation with ROK on Pyro R&D for the first time in 2002, including safeguards, electrolytic reduction, and electrolytic refining [24]. In other words, Pyro was excluded from the target to prevent the spread of sensitive technologies for nuclear non-proliferation. However, there were limits to Pyro collaboration between ROK and the US at this time. The Bush administration allowed Korean scientists to participate in joint research of Pyro at US national laboratories, but did not allow "hot" processing of Pyro using SNF in ROK.

On February 6, 2006, the Bush administration launched the Global Nuclear Energy Partnership (GNEP) to achieve the goal of nuclear non-proliferation as well as expand the use of nuclear energy [25]. If the use of nuclear energy is encouraged, demand on enrichment for nuclear fuel supply and recycling or reprocessing to reduce the disposal burden of SNF may arise. The Bush administration differentiated between nuclear fuel cycle supply states and reactor user states under GNEP. Nuclear fuel cycle supply states provided ENR services to reactor user states, thereby tried to block reactor user states to have an access to sensitive technologies.

However, a number of NNWSs as NPT parties opposed the Bush administration's GNEP, which demanded that the peaceful use of nuclear energy under Article 4 of the NPT be abandoned or compromised as an inalienable right [26]. At the beginning of GNEP, ROK was also cautious about joining in it, concerning that ROK might fall under the category of a reactor user state [27]. In April 2006, at a closed meeting, the US side promised the ROK side to cooperate in developing Pyro technology. ROK recognized the US promise of Pyro cooperation as a nuclear fuel cycle supplier rather than a nuclear reactor user, and joined the GNEP in December 2007 [27]. The Bush administration considered ROK's participation in GNEP as an indication that ROK would not separate pure plutonium through Pyro activities [27].

However, regarding ROK's participation in GNEP in 2007, voices of opposition emerged in the United States, led by nuclear nonproliferation experts [28-29]. They objected from the viewpoint that ROK's participation in GNEP would encourage ROK's Pyro technology development, and that Pyro would be more proliferation resistant than PUREX as a wet reprocessing, but that the effect would not be significant at the state level. They also opposed ROK's pursuit of Pyro, insisting that the Pyro product would have 1/1000 less radioactivity than SNF, which would increase the attractiveness of nuclear diversion. As the Democratic Party, which conventionally emphasizes nuclear nonproliferation, won the Bush administration-led Republican Party in the midterm elections in November 2006, it cut all the budget of GNEP for 2008 FY because GNEP including reprocessing of SNF within the United States could entail nuclear proliferation risks.

As the controversy in the United States was aggravated, the Bush administration, which fell into a "lame duck", began a full review of Pyro cooperation with ROK in 2008. Even for a Pyro that does not extract pure plutonium, the controversy within the United States required new collaboration with ROK in terms of nuclear non-proliferation policy and politics. In October 2008, the Bush administration presented a new framework for collaboration on Pyro to ROK at the ROK-US Joint Standing Committee on Nuclear Energy Cooperation (JSCNEC).

3.2 Cooperation and Restrictions of Pyro Under the Nonproliferation Policy of the Obama Administration

3.2.1 Cancellation of GNEP's Domestic Program in the US and Changes in Pyro Cooperation Between ROK and the US

In a speech in Prague on April 5, 2009, President Barack Obama emphasized the need for immediate and substantive action by countries that violate IAEA safeguards or withdraw from the NPT without any particular reason in order to strengthen nuclear non-proliferation [30]. In addition, President Obama emphasized establishment of an 'international fuel bank' to ensure fuel supply of countries that do not pursue ENR activities.

Details of the nuclear fuel supply assurance can be found in the remarks of former Deputy Secretary of State [31]. He mentioned that it is necessary to ensure that each country does not possess sensitive nuclear technologies based on a stable supply of nuclear fuel, in order to achieve international common security interests of nuclear non-proliferation. The Democratic Party of the US also believed that GNEP could not guarantee nuclear non-proliferation because it included the SNF reprocessing program in the United States. On April 15, 2009, the US Department of Energy (DOE) formalized the cancellation of GNEP's domestic programs by suspending SNF recycling facilities and fast reactor construction in the near term related to GNEP [32].

However, the Obama administration wanted to maintain the international nuclear fuel supply guarantee system under GNEP because it believed that nuclear fuel supply assurance was important for nuclear non-proliferation. In this regard, the Obama administration changed the name of GNEP to the International framework for Nuclear Energy Cooperation (IFNEC) in May 2010 to emphasize international nuclear fuel supply assurance. In other words, the Obama administration tried to secure nuclear non-proliferation by canceling the domestic program of GNEP and to limit individual countries' pursuit of sensitive nuclear technologies through stable supply of nuclear fuel.

The Obama administration's position of changing GNEP to IFNEC acted on a constraint on ROK-US Pyro cooperation. If the Bush administration cooperated with ROK on Pyro under the position that "Pyro is not reprocessing as a fuel conditioning", the Obama administration saw that GNEP including reprocessing was putting a burden on nuclear non-proliferation. Therefore, the Obama administration needed a new direction for Pyro cooperation with ROK. However, the change in the US position was embarrassing from the

Korean point of view, as the full-fledged decision was made in December 2008 to develop Pyro technology, including its domestic demonstration. In this regard, closed meetings were held between ROK and the US. At the 30th JSCNEC held in Washington, DC, USA in October 2010, the Obama administration proposed a new level of advanced joint research plan to ROK [24]. As a follow-up measure, the ROK-US JS was officially launched in April 2011 to assess the feasibility of Pyro [33]. Instead of allowing Pyro activities using SNF in ROK, the United States gave ROK an opportunity to conduct Pyro R&D using SNF in the United States.

It can be seen that the US took two perspectives on Pyro cooperation with ROK during the JS launch process. One is that the Bush administration in its first term did not view Pyro as reprocessing and cooperated with ROK to develop technology that could reduce volume of HLW through SNF recycling in order to expand the use of nuclear energy in the United States. The other is that the Obama administration proposed JS, which actually handles SNF in the United States, as a compromise, delaying the definition of reprocessing of Pyro and permission of Pyro activities in ROK, along with the cancellation of the GNEP program in the United States.

3.2.2 Cooperation and Restrictions of Pyro in the Process of Revising the ROK-US NCA

Amid controversies surrounding the definition of reprocessing of the Pyro since the mid-2000s, ROK and the US entered into the first round of negotiations on October 25, 2010 to revise the existing ROK-US NCA that entered into force in 1973. The existing ROK-US NCA was concluded in 1973 to introduce Kori Unit 1 as the first NPP of ROK in 1978, between the ROK as a unilateral recipient and the US as a unilateral supplier.

However, when negotiations began to revise the existing ROK-US NCA in October 2010, ROK was operating 21 NPPs, the 6th largest in the world [34]. The existing ROK-US NCA had to be revised to reflect ROK's changed status in the nuclear energy field, which was clearly different from that of the 1970s. ROK's goal of revising the ROK-US NCA can be seen in an interview with a government official, the ambassador in charge of the ROK-US NCA, who led the negotiations from the second to the final round [35]. He set the three goals to revise the ROK-US NCA: securing safe and effective management options of SNF including Pyro; a guarantee of stable nuclear fuel supply including enrichment; and retransfer procedures for smooth NPP exports, as a supplier country that exported NPPs to the UAE in 2008.

The role model of ROK to revise the ROK-US NCA can be found in US-Japan NCA amended in the 1988. In the 1988 US-Japan NCA, the Reagan administration allowed Japan, an ally, to enrich less than 20% ^{235}U and extract pure plutonium for reasons such as Japan's advanced nuclear technology, impeccable record of non-proliferation and nuclear transparency, and possession of a delicate mid- to long-term nuclear energy program [36]. In particular, the Reagan administration allowed activities in future ENR facilities, as well as ENR facilities owned by Japan at the time of the revision of the US-Japan NCA.

However, the Obama administration did not treat ROK, like Japan, which did not have enrichment and reprocessing facilities, in the context of nuclear non-proliferation policies such as GNEP's transition to IFNEC. In March 2011, a government official, who was the working-level representative of the United States for the revision of the ROK-US NCA, said, "Pyro is not plutonium alone, but 'full pyro', which includes electrorefining and electrowinning that can separate nuclear materials, is reprocessing" [37]. He also said, "The US DOE did not say that "Pyro is reprocessing" five years ago when it was about to start cooperation with ROK on Pyro, but it has changed its position that the product of Pyro has become dangerous from a nuclear proliferation point of view". His remark was the first case in which the US government announced that Pyro is defined as reprocessing. It means that the US is difficult to immediately allow Pyro to ROK. At the end of negotiations on the revision of the 2015 ROK-US NCA, there were media reports that the US called on ROK to reflect the Joint Declaration, in which the South and North Korea agreed not to possess ENR facilities [38].

The difference in positions between ROK and the US resulted in an agreement not being reached despite the expiration of the existing ROK-US NCA in May 2014. In the end, ROK and the US pursued last-minute negotiations. As a result, the new ROK-US NCA, which completely replaced the existing ROK-US NCA, went into effect in November 2015. The new 2015 ROK-US NCA was not at the level of the US-Japan NCA, but granted ROK programmatic consent or long-term advance consent for the existing Pyro research facilities of ROK for pretreatment and electrolytic reduction as a step before separation of nuclear material. Instead, the US provided ROK with a pathway in the new ROK-US NCA which it could be granted in the future [39]. The US deferred a decision on wherher to grant of long-term advance consent to the Pyro after the JS, considering that the full Pyro accompanying the separation of nuclear material is reprocessing, under the US non-proliferation policy of preventing the spread of sensitive technologies.

4. Conclusion

As of April 2023, ROK has joined all international nuclear non-proliferation regimes, including the NPT, IAEA, NSG and CPPNM, and is faithfully fulfilling its nuclear non-proliferation obligations. ROK has been developing Pyro technology that can alleviate the disposal burden of SNF that is piling up for the peaceful use of sustainable nuclear energy. Owing to the intrinsic feature of dry processing technology, Pyro cannot extract pure plutonium that can be directly used for nuclear weapons, so it is a technology that is more proliferation resistant than reprocessing of the PUREX as a wet processing.

The goal of US non-proliferation policy is to prevent the proliferation of sensitive technologies including ENR. Although the US has continued to cooperate with ROK on Pyro since 2000s, the US nuclear non-proliferation policy turned out to be a major obstacle limiting ROK's Pyro activities. The Bush administration cooperated with ROK on Pyro for the first time from the standpoint that Pyro is not reprocessing in the process of expanding the use of nuclear energy and demonstrating SNF recycling within the US under the GNEP. However, the Obama administration viewed Pyro as a form of reprocessing in the process of revising the ROK-US NCA, and did not grant long-term advance consent to the full Pyro process.

Until now, no agreement has been reached between ROK and the US whether Pyro is defined as reprocessing. The conflict between ROK and the US over Pyro is because ROK views Pyro as a technology with excellent nuclear non-proliferation properties, unlike PUREX, while the US views otherwise. However, if Pyro activities of ROK are restricted under voluntary compliance with the Joint Declaration, no country will agree to a commitment like ROK in the future. Only when activities for peaceful purposes are guaranteed to countries that join all international nuclear non-proliferation regimes, such as ROK, and faithfully abide by their obligations, other countries will perform peaceful activities within the international nuclear non-proliferation regime, not outside it.

In this sense, the US should prepare new nuclear non-proliferation policy for advanced fuel cycle technologies including Pyro with excellent nuclear non-proliferation properties. Given that nuclear proliferation has hitherto occurred outside the international non-proliferation regime, the US should establish the criteria that allow advanced nuclear fuel cycle activities for peaceful purposes to countries that faithfully comply with their nuclear non-proliferation obligations as a member of all international nuclear non-proliferation regimes. The criteria can include enhanced proliferation resistant technology that are difficult to directly use for nuclear weapons, and the feasibility and economic viability of nuclear fuel cycle in accordance with the scale of NPPs, along with condition of the advancement of nuclear technology, nuclear transparency and reliability, and the possession of delicate mid- to long-term nuclear energy programs proposed in the US-Japan NCA.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgements

I would like to thank Jin Shin of Chungnam National University, Bong-geun Jun of Korea National Diplomatic Academy, and Kwang Seok Lee of Korea Atomic Enegy Research Institute. This paper was supported by the National Research Foundation of Korea (NRF) funded by the Korean Government (Ministry of Science and ICT) (RS-2022-00155169).

REFERENCES

[1] Korean Government. October 18 2021. "Final Goal of Government Carbon Neutrality, 40% Reduction by 2030, Zero Net Emissions by 2050." Republic of Korea Policy Briefing Homepage. Accessed May 1 2023. Available from: https://www.korea.kr/news/policyNewsView.do?newsId=148894458.

[2] International Atomic Energy Agency. "Power Reactor Information System (PRIS)." IAEA Homepage. Accessed May 1 2023. Available from: https://pris.iaea.org/pris/countrystatistics/countrystatisticslandingpage.aspx.

[3] Korean Government. May 2 2022. "110 National Agenda of the Yoon Seok-Yeol Administration." Republic of Korea Policy Briefing Homepage. Accessed May 1 2023. Available from: https://www.korea.kr/archive/expDocView.do?docId=39973.

[4] Korean Government. January 12 2023. "Final Version of the 10th Basic Plan for Electricity Supply and Demand (2022~2036)." Republic of Korea Policy Briefing Homepage. Accessed May 1 2023. Available from: https://www.korea.kr/briefing/pressReleaseView.do?newsId=156547521.

[5] Korean Government. September 20 2022. "Draft Disclosure of K Taxonomy including NPPs." Republic of Korea Policy Briefing Homepage. Accessed May 1 2023. Available from: https://www.korea.kr/briefing/policyBriefingView.do?newsId=156526972.

[6] J.H. Lee. October 10 2022. "Nuclear Power Reemerges as a Bastion of Energy Security Amid Carbon Neutrality and Shock From War in Ukraine." Chosun Biz. Accessed May 1 2023. Available from: https://biz.chosun.com/economychosun/coverstory/2022/10/10/KKJ4JJAZEVCI3FFEGR4JBBSIKQ/.

[7] S.H. Kim. February 10 2023. "Hanbit NPP, Storage Facility Saturation After 7 Years, 1~2 Years Ahead." Hankyung Homepage. Accessed May 1 2023. Available from: https://www.hankyung.com/economy/article/202302108225i.

[8] J. Lee, K. Kim, I. Kim, H. Ju, J. Jeong, C. Lee, J.W. Kim, and D.K. Cho, "High-efficiency Deep Geological Repository System for Spent Nuclear Fuel in Korea With Optimized Decay Heat in a Disposal Canister and Increased Thermal Limit of Bentonite", Nucl. Eng. Technol., 55(4), 1540-1554 (2023).

[9] Korea Energy Information Culture Agency. "Overseas Cases of Spent Fuel Disposal Legislation." Energy Policy Communication Center Homepage. Accessed Jun. 16 2023. Available from: https://www.e-policy.or.kr/global/list.php?admin_mode=read&no=5734&make=&search=&page=1&prd_cate=1.

[10] J. Hong, Y.Z. Cho, and M.H. Yang. Technology Development to Safety Manage Spent Nuclear Fuel With our own Hands, Korea Atomic Energy Research Institute Report, 15, Nuclear Policy Brief Report 2020-03 (2020).

[11] Korean Government. December 22 2008. "Future Nuclear R&D Blueprint Announcement as a New National Growth Engine." Office for Prime Minister Homepage. Accessed May 2 2023. Available from: https://www.opm.go.kr/flexer/view.do?ftype=

hwp&attachNo=121336.

[12] Korean Government. December 27 2021. “The 10th Nuclear Power Promotion Committee Held.” Office for Prime Minister Homepage. Accessed May 2 2023. Available from: https://www.opm.go.kr/flexer/view.do?ftype=hwp&attachNo=112417.

[13] International Atomic Energy Agency. IAEA Safeguards Glossary 2001 Edition, IAEA Report, 41, International Nuclear Verification Series No. 3 (2002).

[14] International Atomic Energy Agency. October 18 2019. “Communication Received From the Permanent Mission of Kazakhstan to the International Atomic Energy Agency Regarding Certain Member States’ Guidelines for the Export of Nuclear Material, Equipment and Technology.” IAEA Homepage. Accessed Apr. 30 2023. Available from: https://www.iaea.org/sites/default/files/publications/documents/infcircs/1978/infcirc254r14p1.pdf.

[15] A. Andrews. Nuclear Fuel Reprocessing: U.S. Policy Development, Congressional Research Service Report, 1, RS22542 (2008).

[16] U.S. Government Publishing Office. June 28 2023. “Atomic Energy Act of 1954, as Amended Through P.L. 117-286, Enacted December 27, 2022.” U.S. Government Information. Accessed Jun. 30 2023. Available from: https://www.govinfo.gov/content/pkg/COMPS-1630/pdf/COMPS-1630.pdf.

[17] K.B. Oh, K.S. Lee, D.J. Lee, B.Y. Lee, I.H. Cho, and H.S. Ko. A Study on the Establishment of a Standard Nuclear Cooperation Agreement and the Revisions of Existing Nuclear Cooperation Agreement in Korea, Korea Atomic Energy Research Institute Report, 22, KAERI/RR-1689/96 (1997).

[18] Korean Government. April 15 2016. “NSSC introduced No-Notification Inspections by IAEA, Nuclear Transparency.” Republic of Korea Policy Briefing Homepage. Accessed Apr. 30 2023. Available from: https://www.korea.kr/news/interviewView.do?newsId=148812240.

[19] M.H. Yang, B.W. Lee, K.B. Oh, H.M. Lee, H.S. Ko, J.S. Ryu, and K.S. Lee. The Handbook of Nuclear Non-proliferation, Korea Atomic Energy Research Institute Report, 37-54, KAERI/TR-2543/2003 (2003).

[20] Ministry of Foreign Affairs. November 14 2007. “Key Issues Relating to the Iranian Nuclear Issue.” Mofa Homepage. Accessed Apr. 30 2023. Available from: https://mofa.go.kr/www/brd/m_3989/view.do?seq=307739&srchFr=&srchTo=&srchWord=&multi_itm_seq=0&itm_seq_1=0&itm_seq_2=0&company_cd=&company_nm=&page=7.

[21] Natural Resources Defense Council. February 12 2004. “The Bush Proposals to Curb Nuclear Proliferation.” NRDC Homepage. Accessed Apr. 9 2023. Available from: https://www.nrdc.org/press-releases/bush- KAERI/RR-2867/2007 proposals-curb-nuclear-proliferation.

[22] The White House. February 11 2004. “President Announces New Measures to Counter the Threat of WMD.” The White House Archives. Accessed Apr. 9 2023. Available from: https://georgewbush-whitehouse.archives.gov/news/releases/2004/02/text/20040211-4.html.

[23] National Energy Policy Development Group. May 16 2001. “National Energy Policy.” Nuclear Regulatory Commission Homepage. Accessed Apr. 30 2023. Available from: https://www.nrc.gov/docs/ML0428/ML042800056.pdf.

[24] J.S. Yoon. Research on the Enhancement of Korea-US Cooperation of Advanced Fuel Cycle, Korea Atomic Energy Research Institute Report, 18, 2009-0094184 (2011).

[25] U.S. Department of Energy. February 6 2006. “The Global Nuclear Energy Partnership: Greater Energy Security in a Cleaner, Safer World.” U.S. DOE Homepage. Accessed Apr. 30 2023. Available from: https://www.energy.gov/articles/global-nuclear-energy-partnership-0.

[26] J.S. Ryu, B.W. Lee, H.M. Lee, H.S. Ko, K.S. Lee, and

H.R. Kim, "Implications and Prospects of the GNEP", Proc. of the 2008 Korean Nuclear Society Spring Meeting, 863-864, May 29-30, 2008, Gyeongju.

[27] B.W. Lee, H.M. Lee, H.S. Ko, J.S. Ryu, K.B. Oh, M.H. Yang, and K.S. Lee. A Study on the Nuclear Foreign Policy, Korea Atomic Energy Research Institute Report, 47-65, KAERI/RR-2867/2007 (2007).

[28] F.N. von Hippel. March 2010. "South Korean Reprocessing: An Unnecessary Threat to the Nonproliferation Regime." Arms Control Today. Accessed Apr. 2 2023. Available from: https://www.armscontrol.org/act/2010_03/VonHippel.

[29] E. Lyman and F.N. von Hippel. April 2008. "Reprocessing Revisited: The International Dimensions of the Global Nuclear Energy Partnership." Arms Control Today. Accessed Apr. 2 2023. Available from: https://www.armscontrol.org/act/2008-04/features/reprocessing-revisitedthe-international-dimensions-global-nuclear-energy.

[30] The Guardian. April 5 2009. "Barack Obama Launches Doctrine for Nuclear-free World." The Guardian News. Accessed Apr. 1 2023. Available from: https://www.theguardian.com/world/2009/apr/05/nuclear-weapons-barack-obama.

[31] Carnegie Endowment for International Peace. April 7 2009. "2009 Carnegie International Nonproliferation Conference." Carnegie Endowment for International Peace Homepage. Accessed Apr. 9 2023. Available from: https://carnegieendowment.org/2009/04/07/2009-carnegie-international-nonproliferation-conference-event-1597.

[32] D. Horner. May 2009. "Part of GNEP Officially Canceled." Arms Control Today. Accessed Apr. 9 2023. Available from: https://www.armscontrol.org/act/2009-05/part-gnep-officially-canceled.

[33] M. Holt. June 25 2013. "U.S. and South Korean Cooperation in the World Nuclear Energy Market: Major Policy Considerations." Congressional Research Service. Accessed Apr. 9 2023. Available from: https://sgp.fas.org/crs/row/R41032.pdf.

[34] Y.I. Kim and E.J. Yu. November 8 2010. "Issues and Tasks of the 1st Negotiation to Revise Korea-US Nuclear Cooperation Agreement." National Assembly Research Service. Accessed Apr. 10 2023. Available from: https://www.nars.go.kr/report/view.do?page=197&cmsCode=CM0018&categoryId=&searchType=&searchKeyword=&brdSeq=1089.

[35] R.B. Park. May 18 2015. "New Korea-US Nuclear Cooperation–Meaning and Direction." Nuclear Industry. Accessed Apr. 10 2023. Available from: https://www.kaif.or.kr/upload/nuclear1/20150701161215_e9b9af74.pdf.

[36] J.H. Jeon, "Decision Making Process of US-Japan Negotiation: Analysis of Negotiation Process in the Amendment of the US-Japan Nuclear Cooperation Agreement", J. Int. Area Stud., 11(2), 23-49 (2002).

[37] M. Hibbs, H. Alkaabi, S. Snyder, and R. Stratford. March 29 2011. "U.S. Nuclear Cooperation: How and With Whom?" Carnegie Endowment for International Peace. Accessed Apr. 10 2023. Available from: https://carnegieendowment.org/2011/03/29/u.s.-nuclear-cooperation-how-and-with-whom-pub-43479.

[38] Yonhap News. June 17 2015. "U.S. Requests to Reflect 'Declaration on the Denuclearization of the Korean Peninsula' in the Korea-US Nuclear Agreement." Yonhap News Homepage. Accessed Apr. 10 2023. Available from: http://www.yna.co.kr/view/AKR20150617010500071.

[39] B.G. Jeon. May 6 2015. "The New ROK-U.S. Nuclear Cooperation Agreement: Its Significance and Tasks." Institute of Foreign Affairs and National Security. Accessed Apr. 9 2023. Available from: https://www.ifans.go.kr/knda/ifans/eng/pblct/PblctView.do?csrfPreventionSalt=null&pblctDtaSn=12384&menuCl=P09&clCode=P09&koreanEngSe=ENG&pclCode=&chcodeId=&searchCondition=searchAll&searchKeyword=Nuclear&pageIndex=1.