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Future Plans About the High-Level Radioactive Waste Disposal

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ABSTRACT

The Biden Administration officially advocated nuclear energy to successfully achieve a net-zero carbon economy for America by 2050. South Korea also abolished the 'nuclear power phase-out' policy', promoting the expansion of nuclear power because of its high efficiency. Despite the preference for utilizing nuclear energy is growing, limitations on expanding the use of nuclear power and insisting on it as a solution for future energy shortages currently exist because there are no effective treatments for the 'high-level radioactive waste' other than accumulating in the reactor. Thus, to find effective treatment technology, I reviewed 'pyroprocessing' and 'vitrification' as possible technologies to solve the nuclear waste problem. I deeply searched the process, advantages, problems, and prospects of the two technologies based on research papers and the 'Korean Nuclear Energy Newspaper', and organized them in a table. As a result, I derived an ideal high-level radioactive waste treatment method and predicted that the outlook for nuclear energy will be positive.

Introduction

In December 2021, the Biden administration signed an executive order to achieve 'Net-Zero Carbon Economy' by 2050, specifying nuclear power as an 'eco-friendly power' with zero carbon emissions (Herman, 2021). With this, the U.S. officially put an end to the 'nuclear power phase-out policy'. It identified nuclear power as a 'future clean energy' to replace conventional thermal power generation, and IAEA claimed to increase projections for nuclear power use by 2050 (IAEA, 2021). Due to the prejudice that existing nuclear power is 'dangerous', 'expensive', and 'inefficient', most nations including South Korea have boycotted utilizing nuclear energy. However, continuous research proved that nuclear power plants are safe enough to withstand the Richter 7.0 earthquake (Chosun, 1995) and have much better efficiency having a facility area of $0.92km^2$ per GW than other eco-friendly power sources (wind power-15.62). Showing that nuclear plants are efficient and safe, a Reuters and Ipsos survey indicated nearly half of Americans (45%) now support nuclear power. However, this survey also reflects that there are still people who are skeptical about nuclear energy despite these excellent abilities, and many misunderstandings have been solved. The main reason to oppose it is because of the lack of high-level radioactive waste disposal methods. Although nuclear energy has superiority in efficiency, power supply stability, and greenhouse gas emission over other power sources, scientists are unable to properly dispose of high-level radioactive waste, accumulating this dangerous waste inside the power plants. Because of this, the EU Green Taxonomy insisted that nuclear energy could be admitted as 'Eco-friendly power generation' only if the World Nuclear Association proposes a concrete plan to safely dispose of high-level radioactive waste (Naschert, 2022). In the era of reviving nuclear energy with the Biden administration's support, this paper will deeply review current nuclear waste disposal methods and future technologies to solve high-level radioactive waste problems.

High-Level Radioactive Waste

High-level radioactive waste is harmful junk spouting radiation created after a fission reaction, which generates energy. This waste is unrecyclable because they have a half-life of more than 20 years and over 4000 Bq per gram (KRWA). Furthermore, as long as radioactive isotope atomic nuclei exist, radiation cannot be prevented by any chemical treatment, defining this as toxic waste unable to treat and dispose of. Since the operation of the first nuclear power plant in Obninsk, Russia in 1954, scientists have not been able to find a way to solve this problem for 868 years. The effective period of radioactivity (years spent to return to the natural level) varies by elements, but Pu-239 has a half-life of 24,000 years that could continuously pollute the Earth if it is not enclosed with thick concrete. Nuclear power generation inevitably produces high-level radioactive waste consisting of Tc, Ce, Cs, Sr, and I because it utilizes fission reactions of neutrons and U-235. Consequently, to increase the usage of nuclear plants, developing a technology to efficiently reduce and safely dispose of high-level radioactive waste produced in proportion to the amount of electricity generated is essential.

Current High-level radioactive waste disposal method

Unfortunately, there is no practical way to dispose of nuclear waste with potent radioactivity. Unlike the low or intermediate radioactive waste that could be disposed of by putting them inside a thick concrete drum (thickness 10cm, volume 75 m^3) and burying it underground, high-level radioactive waste is too dangerous and powerful to store underground. Returning to its natural level, it will constantly release high temperatures and lethal doses of radiation, restricting the near-surface disposal method. So, Korea Hydro & Nuclear Power Co., Ltd. Since there is still storage space left in the alighting site, nuclear waste is being stored in water with a large amount of boron, a neutron absorber (Yi, 2006). This means if this storage becomes full, Korea could not activate nuclear power plants because they are not able to dump nuclear waste. To solve this problem, IAEA devised a ‘deep geological disposal method’ and landfilling HLW at a depth of 100m or more, but it was very difficult to search for an area that satisfies both safety and groundwater infiltration conditions for over 100,000 years from external changes. In Finland, ‘Onkalo’, the place that applied the deep geological disposal method, has been constructed and scheduled to be operated in 2022 (El-Showk, 2022), but currently, there are no practical methods that can fulfill the EU’s demand.

If the Biden administration actively supports nuclear power and IAEA implements the planned building of at least 100 power plants by 2040s, the absolute amount of high-level radioactive waste will significantly increase and the disposal problem will become even more severe. It will be very difficult to select alternative areas that could be used as nuclear waste storage, and also external problems such as opposition from civic organizations will be triggered too. So, the lack of high-level radioactive waste disposal technology will deteriorate the development of the nuclear power industry. The solution is urgent and essential.

Planned High-Level Radioactive Waste Disposal Method

At present, scientists have admitted that it is impossible to convert nuclear waste into environmentally friendly materials, so they are concentrating on developing practical technologies that can minimize its volume and radiation toxicity. When an effective and specific waste treatment is presented, nuclear energy could be officially approved by the EU as eco-friendly green energy, thereby overcoming the skeptical opinions of the general public. Therefore, I reviewed ‘*Pyroprocessing*’ and ‘*High-level radioactive waste vitrification’*, which have good potential and are highly feasible.

Pyroprocessing Technology

Pyroprocessing technology is a result of joint research by South Korea and the U.S. for over 10 years (Lee, 2021). Most of the spent nuclear fuel consists of uranium oxide and plutonium, produced when a fission reaction occurs in light water reactors, and oxygen combined with Ur-235. In this situation, 'pyroprocessing' is a dry reprocessing technology that enables reusing the spent nuclear fuel by reducing, and burning remaining uranium, plutonium, and minor actinide at once through a sodium-cooled fast reactor to produce electricity.

Figure 1. Korean scientists experimenting 'pyroprocessing' technology. (Lee,2021)

Pyroprocessing Process

Head-End Process is the first step of reprocessing technology. This process is meant to prepare the spent fuel for extraction. According to 'The European Nuclear Society', the specific steps for this technology are feeding these elements into a sectioning machine and cutting the spent fuels into adequate pieces (5cm) for 'pyroprocessing'. Then, dissolve the irradiated spent fuel pieces into a dissolution device concentrated with nitric acid. Finally, the spent fuels (U, PU… etc) are purified so they could be usable in an 'electrochemical reduction' (Lee, 2013).

After the Head-End process, put spent fuel in Li2O-LiCl salt dissolved liquid. Then similar to the principle as water divides into oxygen and hydrogen when electricity is applied, pure uranium can be extracted by cathode reaction using electricity from purified uranium oxide, which is the majority of the high-level radioactive waste. The specific uranium oxide electrolytic reduction process is as follows.

$$UO_2 + 4e^- \rightarrow U + 2O^{2-}$$
$$Li^+ + e^- \rightarrow Li$$
$$UO_2 + 2yLi \rightarrow xU + yLi_2\ (or\ 2yLi^+ + yO^{2-})$$

Converting metal oxides directly into their parent metals was conventionally impractical, but the FFC-Cambridge process created by Chen et al. enabled applying this electrochemical reduction in Uranium dioxide. When the electrochemical reduction process has been finished, there will be pure metal fuel (U, Pu, Np, Am, etc) at least 97% oxygen being eliminated without salt loss, and the oxygen gas is discharged out of the tube. So, the electrochemical reduction process enables reusing products after the fission reaction-originally considered as high-level radioactive waste. Spent light water reactor fuel consists of actinides (U, Pu, Np, Am, etc). noble metals (Zr, Mo, Ru, Tc, Pd, Rh, Cd, Ag, etc), rare earth (Nd, Ce, La, Pr, Sm, Y, Gd, Dy, etc), and salt-soluble fission products that are melted in Li2O-LiCl aqueous solution. Nonetheless, actually, 71-82% of fission products are dissolved, and other products remain in fuel pellets with various actinides undissolved. In other words, the electrochemical process managed to eliminate 97% of oxygen, but there are still impurities left that distract from extracting pure uranium. Thus, uranium, transuranic elements, and residual fission products are heated to 500°C in LiCl-KCl-UCl3 solution to dissolve the elements and products in the anode. This ultimately leaves only pure Uranium and other products combined (Choi & Jeong, 2015). In conclusion, pyroprocessing could extract pure uranium, which is the main source of nuclear power, but cannot isolate pure Pu (Woo, 2020).

After going through 1-3 steps, most of the uranium oxide in the high-level radioactive waste is reduced and purified so that it can be directly reused in a nuclear reactor. Also, trans uranium elements, such as americium, that have a heavier mass than uranium and dissolved Pu could be recycled as sources for SFR. Since 2011, joint research between South Korea and the U.S. has been in progress. Pyroprocessing might feel like theoretically a practical and perfect technology, but the research was once halted during 2018-2020 due to the controversy surrounding the technology (Kim, 2021), opposition from civic groups, and budget cuts in Korea. Why did ‘Pyroprocessing’, which is an ideal reprocessing technology, continue to be questioned and stopped for 3 years? These questions led to an in-depth study of the advantages and problems of this technology.

Advantages & Problems of Pyroprocessing

According to the research results, the use of pyroprocessing technology can reduce the area of a high-level radioactive waste treatment plant to approximately 1/100, usage of existing raw materials by 1/20, and neutralize the toxicity of nuclear waste to less than 1/1000. Also, it is possible to increase the utilization efficiency of uranium by more than 100 times. Additionally, existing disposal technology dumped all the uranium oxide because they were considered useless, applying pyroprocessing enables reusing 95% of the spent fuel (Jeon, 2009). If this technology actually is applied, it will have a great comparative advantage from environmental and economical perspectives. Lastly, unlike the other planned reprocessing technologies that can extract pure Pu, pyroprocessing blocked the possibilities of extracting pure Pu because Pu is combined with neptunium, americium, and curium. Thus, it excludes the possibility of abusing this reprocessing technology to create nuclear weapons. If the pyroprocessing technology is applied in South Korea and the U.S., it will dramatically reduce the time to eliminate the radiotoxicity of spent fuel from 30 million years to 300 years (kemco, 2015). Consequently, it could solve the current problem, the absence of a high-level radioactive waste treatment method (Ji & Al-Dbissi, 2018).

One of the main reasons opposing the pyroprocessing application is the possibility of illegal nuclear weapon development, which is directly conflicting with its advantage. The current pyroprocessing process cannot extract the pure Pu, the opponents claim that it could be easily adjusted and exploited to create weapons-grade plutonium (Palmer, 2015). The main 3 nations that contributed to this technology are the U.S., South Korea, and Japan. If South Korea and Japan developed nuclear weapons using this technology, negative political tension will be invoked in Eastern Asia. Also, pyroprocessing is a ‘reprocessing’ technology not a nuclear waste removal technology. It could solve the long-term storage issue and greatly increase nuclear power efficiency, but the nuclear waste will still accumulate. In other words, pyroprocessing could not solve the fundamental nuclear waste accumulation problem. Finally, the research team is constantly enhancing the technological completion through various experiments, but the stability and economic feasibility have not yet been sufficiently verified.

Pyroprocessing is the most efficient and promising high-level radioactive waste reprocessing technology developed by 2022. A deeply developed fuel cycle will practically relieve the environmental problems degrading nuclear energy’s implementation by satisfying proliferation resistance and recycling 95% of original nuclear fuel. Due to the positive prospect, not only the U.S. and France, which are the developed countries in the nuclear area, but also Asian nations like China and India are investigating the development of this technology. Also, research has been continued on electrorefining, electrochemical reduction, injection casting, and the reductive extraction of actinides, so the efficiency of Pyroprocessing will be enhanced (Inoue & Koch, 2008). Thus, if safety has been proven and commercialized, it will be the ideal method to effectively reduce nuclear waste. Also, the fact that it is not exclusive to European nations and the U.S. is a big advantage. Many Asian countries including South Korea and Japan can develop this technology, so the international nuclear waste problem could be peacefully solved without diplomatic conflict. Nevertheless, the possibility of abusing it to create nuclear weapons is a serious concern that pyroprocessing is confronted with. According to an official announcement by Korea Hydro & Nuclear Power, pyroprocessing absolutely cannot extract pure Pu, the research team must strengthen the safety device that proves to the creation of nuclear weapons are impossible even with any other further steps. Internationally, they need to show that pyroprocessing continuously complies with the provisions of the 'Budapest Guarantee Memorandum' (Wikipedia, 2022). If the experiment results completely guarantee the stability of the technology and the impossibility of manufacturing nuclear weapons during the 5-10 years of the development process, I strongly support the use of pyroprocessing because it could solve the existing high-level radioactive waste disposal problem.

High-Level Radioactive Waste Vitrification

Vitrification is not a nuclear waste reprocessing technology like pyroprocessing, and it is not a method that could reduce the absolute amount of waste. In order to solve the radioactivity problem, the nuclide itself that emits radiation must be removed, but this is theoretically impossible. Thus, researchers are focusing on 'reducing' the volume of high-level radioactive waste to maximize the efficiency of the storage. Vitrification is a method that minimizes the volume by confining radionuclides inside the glass structure (Harrison, 2014), (Kim, 2012). This technology was originally used to treat low and intermediate-level radioactive waste. However, on September 11, 2021, in China, the first vitrification facility for high-level radioactive waste was operated at CAEA, proving vitrification is not a theoretical technology (Brown, 2021). Currently, many European nations started to develop vitrification to extend the storage usage period.

Vitrification Process

The vitrification of high-level radioactive waste uses the special properties of borosilicate glass. As the boron reacts with the glass, a void is created between the bonds of SiO2, which can contain particles, including radionuclides that emit strong radiation. Some people might worry that this technology is dangerous because radionuclides could escape. However, radionuclides become chemically very stable by ionic bonding with oxygen in the empty space between the glass structures. This indicates the nuclides never escape even if the glass breaks and shatters (Song, 2020), (Song & Kim, 2004).

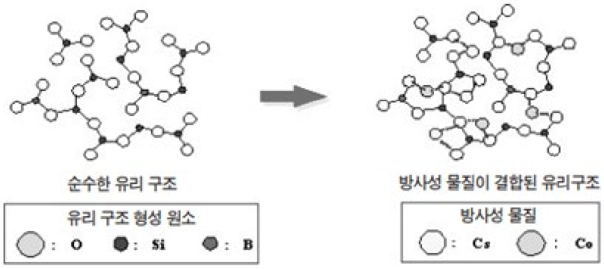

Figure 2. Visualization of 'pure glass structure (left)' and 'glass structure combined with radioactive material(right)' (Kim, 2004)

To use this special property, the first step of vitrification is melting the glass. In 1994 Japan, they created molten glass by the heating furnace to 1350 °C with an induction current using high frequency. However, since the hot crucible melter used in Japan and France had low economic efficiency due to unnecessary power consumption, Korea Radioactive Waste Agency (KRWA) cooperated with Korea Plasma Institute and developed its own furnace that could melt the glass at a relatively low temperature (1050 °C) by directly heating the furnace. The coil is directly wrapped around the furnace, and the operator sends alternating high-frequency current to a coil that creates an induced current, which essentially creates heat to melt the boron silicate glass (Kim, 2004). According to a 2010 Stanford university study, it is possible to successfully melt the glass for vitrification even at approximately 1000 °C (Thomson, 2010).

Once the glass has been fully melted, the operator feeds high-level radioactive waste into the furnace. When the waste contacts glass, combustion and pyrolysis happen, and waste is separated into inorganic substances and radionuclides. The vitrification process itself is simple compared to low and intermediate-level radioactive waste because high-level radioactive waste's chemical composition is always constant. However, since the level of radiation generated in this process is very high, remote facilities and safety devices must be well established.

According to KRWA, the thermal energy transferred to the nuclear waste decrease as the internal melting furnace gets filled, so the supply speed should also slow down. Then, when the container is filled and the molten glass and nuclear waste (mainly Cs-137, Co-60) are uniformly intermingled at a constant temperature, the operator cuts the current and produces the solid glass crystal by cooling.

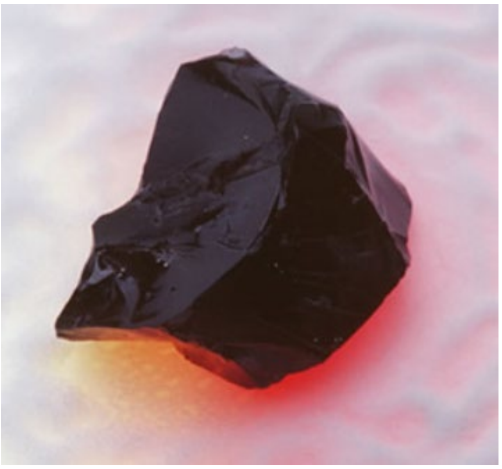

Figure 3. Crystals that are produced after high-level radioactive waste vitrification (Cho, 2020)

These crystals, formed at the top part of the furnace, are collected into a container because of the gravitational force. Since inorganic elements including water that were partially present in nuclear waste, are removed from radionuclides during pyrolysis, glass crystals through vitrification are dry.

Advantages & Problem of Vitrification

The great advantage of the technology to vitrify high-level radioactive waste is that it can dramatically reduce the volume of nuclear waste, thereby solving the problem of residual space in the waste saturated because of the long-term use of nuclear power plants. In the case of Korea, a plan to add four additional units was established by 2030, but the plan is currently stopped because nuclear waste-filled 60-80% of the storage (Choi, 2021). However, if vitrification is used, it can reduce 70-80% of nuclear waste volume (Jantzen 1995). Also, after research, it is found that it can be reduced max 1/23 of waste's original volume (Kim, 2000). In other words, up to 23 wastes can be stored comfortably in a narrow space that could only fit into one waste drum in the past. Also, since there is no special additional process except for the melting and cooling process, developing this technology is relatively easy so many nations could promote vitrification, and the storage cost is dramatically decreased because the volume is minimized. These advantages lead to more public acceptance and improve negative perceptions of nuclear energy. Finally, high-level radioactive waste can be stored and disposed of very safely. Radionuclides can be stabilized in the form of vitrification due to the characteristic of the borosilicate glass that traps nuclides into the empty space between the chemical bonds. Concrete burial methods have a risk of contamination of groundwater by erosion of containers due to groundwater erosion and leakage of radioactivity. However, radionuclides cannot escape from the crystal even if the glass cracks. As a result, vitrifying the waste is the safest way to handle high-level radioactive waste.

Although vitrification dramatically reduces the volume and has subtle effects on the surrounding environment, this technology does not ‘remove’ the radionuclides. Same as pyroprocessing, this technology could slow down the accumulation but cannot solve the fundamental problem. In addition, vitrification activates the corrosion of the container, which might trigger a risk of radiation leakage (Jantzen, 1995). The safety-related studies only tested possibilities of leaking occurring at the crystals. However, the drum enclosing the crystals could corrode as time passes and the crystals themselves could be exposed to the outside. This invokes the risk of leakage. Also, the current glasses cannot handle large amounts of MoO_3 and noble metals that are produced from secondary waste streams, increasing process time and material costs (Layton, 2020). From an economic perspective, current vitrification technology is inefficient. The advantage introduced vitrification could save storage costs because people could store much more waste, the initial cost of this technology is $20B-$36B. Compared with the expense of the method of encasing the radioactive waste with concrete-like grout is $2B-$8B, vitrification is way too expensive (Cary, 2019). Finally, the operation cost is also very high too, which could raise economic concerns for nations adapting to vitrification.

High-level radioactive waste vitrification can solve the storage capacity problem and save the storage cost because it compresses volume up to 1/23 of the current method. In addition, it enables the radionuclides to be stabilized inside the glass crystal by utilizing ion bonding with oxygen. (Kim & Park, 2007), (Wicks, 1986) Also, IAEA and European nations are already using this method for low and intermediate radioactive waste, and safety is guaranteed. Nonetheless, radioactive waste accumulation still exists, so the nations eventually need to find another storage enabling the disposal of vitrified nuclear waste. There is a risk of crystals being exposed to external circumstances because crystals can corrode the drum container over time. From an economic perspective, even though the storage cost is dramatically reduced, developing countries will confront difficulties because their initial and operational costs are higher than current treatment methods. Thus, considering the characteristics of nuclear waste and vitrification, the prospect of this technology is positive when the ‘deep geological disposal method’ is operated and commercialized (Korea Atomic Energy Research Institute, 2017), (WACID).

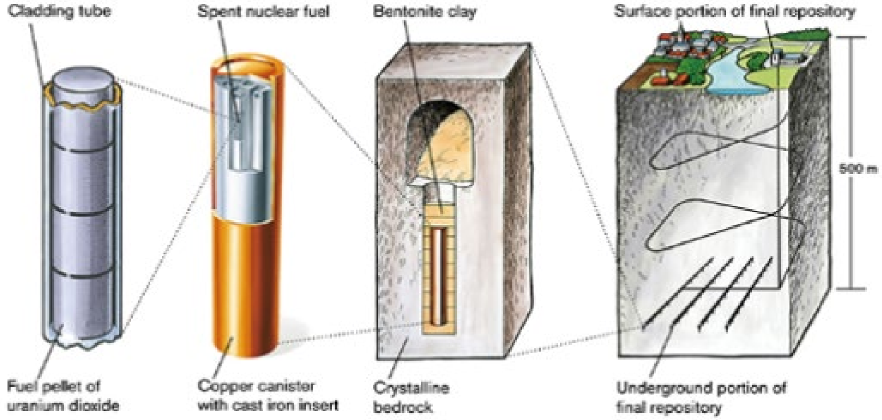

Figure 4. Picture of deep geological disposal method for high-level radioactive waste (Advances in Nuclear Fuel Chemistry, 2020).

The reason the deep geological disposal method, permanently burying the nuclear waste 300-1000m underground, is essential is that these crystals went through vitrification and need a stable place where it could safely store them for at least 10,000 years to remove radiotoxicity and return to a natural level.

Conclusion

I reviewed Pyroprocessing and Vitrification technologies that could potentially solve the problem of lacking storage space and sufficient treatment of high-level radioactive waste. The analyzed data for each technology is as follows.

Table 1. Organized Data of Pyroprocessing and Vitrification.

	Pyroprocessing	Vitrification
Method	Reprocessing the spent fuel	Vitrifying the radionuclides
Technical Advantages	Enables reusing 95% of spent fuel. Prohibited extracting pure Pu (Eliminating possibilities of inventing nuclear weapons) 10,000% Increases Uranium efficiency	Reduces the volume to 1/23 Safely encloses spent fuel Guarantee Safety
Technical Problems	Very low, but the possibility of exploiting 'Pyroprocessing' to invent nuclear weapons exists. Cannot eliminate the radionuclide Unguaranteed Safety	Economically expensive Possibility of corroding the vessel Cannot eliminate the radionuclide
Cost	$1B to end the inventory	$20B-$36B initial cost
Availability Year	2050	Currently Available

To solve the problem of future high-level radioactive waste disposal, I propose using two technologies in phases. If pyroprocessing and vitrification are used together, 95% of waste can be recycled in the primary pyroprocessing and the volume can be compressed up to 20 times in the secondary vitrification process. Therefore, $0.05*1/23*100\approx0.22\%$, and only 0.22% of the existing waste amount need to be treated. Then, store high-level radioactive waste that has undergone two stages in 'Onkalo', which is the first storage that applied the 'deep geological disposal method' in Finland (Posiva). Although there were a few uncertainties with 'Onkalo' in the safety during the experiment, it is the most ideal storage for high-level radioactive waste (Voutilainen, 2014). If the safety of Pyroprocessing and the inability to produce Pure Pu is proven through specific experiments by 2050 (KAERI, 2021), and the construction of Onkalo is completed by 2023, the existing nuclear waste problem could be solved.

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