The status of the U.S HALEU/LEU+ supply program and its implications on the Korean advanced reactor research and development

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1. Introduction

Recently, High-Assay Low-Enriched Uranium (HALEU) and Low Enriched Uranium Plus (LEU+) fuel have drawn a lot of attention for their advantages that improve reactor performance. HALEU is uranium with a concentration of the fissile isotope U-235 between 5 and 20% of the mass of the fuel [1], and LEU+ is a fuel with U-235 concentration between 5% and 10%. The higher enrichment means the fuel assemblies and reactors can be smaller, and reactors don't need refueling as often, which is why many advanced reactors (ARs) including small modular reactors (SMR) and microreactor designs plan to use HALEU or LEU+.

In accordance with the Republic of Korea-United States Nuclear Cooperation Agreement, the Republic of Korea needs the consent of the United States (US) to utilize uranium enrichment technology. Currently, the republic of Korea cannot produce enriched uranium on its own and is 100% dependent on imports. However, the supply and demand environment for enriched uranium is rapidly changing. Rising uranium market prices, high demand for more than 5% enriched uranium, and tight supply are expected to have a significant impact on Korea's supply of HALEU and LEU+ fuels for future AR deployments [2].

Therefore, this study examines the changing environment in the supply and demand of enriched uranium and also examines the lessons that Korea should learn for future deployment of advanced nuclear reactors through an analysis of the US's advanced nuclear reactor deployment strategy and process.

2. Changing Environment in the Supply and Demand of Enriched Uranium

In order to establish a stable enriched uranium supply strategy in Korea, which relies on overseas markets for 100% of its uranium supply, it is necessary to understand the current environment surrounding enriched uranium (see Fig. 1).

2.1 Increasing enriched Uranium market price after the US-Russia conflict

After the incursion of Russia's war against Ukraine, Western governments continue working to reduce Russian revenue sources, including its energy sector exports. However, Russia's nuclear industry was an exception to this due to tight Uranium supplies and high enrichment Uranium prices worldwide [3]. Russia is the world's largest supplier of uranium enrichment services, and approximately 20% of the US' enriched uranium for commercial power generation comes from Russia. This is why the Russian uranium embargo was not considered. However, as the US is considering a ban on uranium imports from Russia, the price of uranium enrichment is currently rising rapidly. Korea's dependence on Russian uranium is also very high at 33.8%. If a global embargo on Russian uranium begins, the impact on Korea's energy security will be significant.

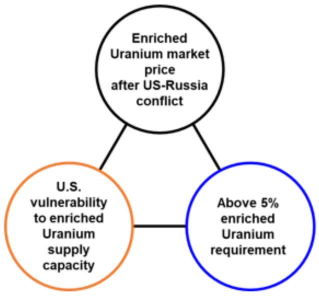

Fig.1. The current environment surrounding enriched Uranium supply and demand

2.2 The U.S. vulnerability to enriched Uranium supply capacity

The "Megatons to Megawatts" project, implemented from 1993 to 2013, allowed Russia to dilute its own highly enriched uranium for nuclear warheads into low enriched uranium for use in US commercial reactors. This increased the US' dependence on enriched uranium from Russia, accelerating the contraction of the US-enriched uranium supply market, and had the unintended consequence of continuing to import enriched uranium from Russia even after the end of the project. The only current uranium enrichment capability in the United States is in Urenco's New Mexico plant, with a capacity of some 4.9 million SWU/yr in 2020, according to World Nuclear Association [4]. Even if 100% of the US' supply capacity is used, only 1/3 of the necessary enrichment services can be met, and 2/3 has to be imported. It takes at least several years to expand an enrichment facility.

2.3 Growing demand for Uranium enriched above 5%

The majority of AR types currently under development around the world require HALEU and LEU+ fuel supplies exceeding 5% enrichment. For example, Accident Tolerant Fuel (ATF) has the advantage of being able to allow higher burnup in a nuclear reactor by utilizing nuclear fuel materials with excellent performance. To fully exploit these advantages, LEU+ with a Uranium enrichment of 5-10% is required. The US Nuclear Regulatory Commission (NRC) is preparing for an increase in concentration of 8% required for the introduction of ATF. In addition, 9 out of 10 AR types supported by the U.S. Department of Energy (DOE)'s Advanced Reactor Demonstration Program (ARDP) require HALEU nuclear fuel with enrichment between 5% and 20%. One of the ARDP programs, Bill Gates' TerraPower Natrium reactor also requires HALEU. However, there is a shortage of local suppliers in the U.S. who can meet the rising demand.

As such, the current environment is very different from the environment that Korea has experienced so far in procurement of uranium enrichment of less than 5%. Currently, there is a very high possibility that Korea may not be able to receive timely supply of uranium with enrichment exceeding 5% in the future, which may affect the demonstration and commercialization of advanced nuclear reactors in Korea.

3. Advanced Reactor Deployment Process in the U.S.

The environment related to enriched uranium discussed above shows that the ability to supply and demand uranium at an enrichment level of 5% to 20% will be a major factor in determining the speed of demonstration experiments and commercialization of advanced nuclear reactors. Therefore, by looking at the current deployment process of advanced nuclear reactors in the US, we will find out what additional efforts the US is making along with preparations for supplying enriched uranium for the deployment of advanced nuclear reactors.

3.1 Framework for Advanced Reactor Deployment

As a result of conducting extensive literature research on the US advanced nuclear reactor deployment process, [4-6] it was analyzed that the U.S. uses a framework consisting of the following four categories for advanced nuclear reactor deployment as shown in Fig. 2.

1	**Advanced Reactor Demonstration Program**	• DOE driven advanced reactor (AR) development programs • ARDP (Advanced Reactor Demonstration Program)
2	**Regulations and Licensing**	• Establishing an efficient and stable regulatory structure that is prepared to license the advanced reactors of the future • Supported by NEICA and NELA
3	**Potential Customer**	• Risk managements for potential customer and investor • Government purchase agreements of long-term power from ARs • Supported by NELA
4	**Fuel Supply (HALEU / LEU+)**	• DOE's contracts with American Centrifuge Operating (ACO), Centrus Energy • HALEU Availability Program (21. 12. 14) • Nuclear Fuel Security Program (2023) • URENCO's Uranium enrichment capability increase (5.5% → 10%) (22.5.23.)
Legislative Activity		• Nuclear Energy Innovation Capabilities Act (NEICA) (18. 9. 28.) • The Nuclear Energy Innovation and Modernization Act (NEIMA) (19.1.14.) • Nuclear Energy Leadership Act (NELA) (19. 3. 27.) • Energy Act of 2020 (20. 12. 29.) • Energy infrastructure Act (21. 11. 15) • Inflation Reduction Act (IRA) (22. 8. 19.) • International Nuclear Energy Act (22. 12. 7)

Fig.2. Framework for Advanced Reactor Deployment

The first is ARDP. The progress of the demonstration program led by DOE has accelerated the deployment of ARs by companies such as TerraPower and X-energy. Second, in terms of regulations and licenses, the U.S. is making efforts to establish efficient regulations in preparation for licensing future advanced nuclear reactors. Third, the US manages risks for potential customers and investors through long-term government purchase contracts for the electricity produced by these future advanced nuclear reactors. And the fourth consists of support for fuel supply for future nuclear reactors. The US government is actively responding to this issue by providing federal subsidies to enriched uranium suppliers such as Centrus Energy and by operating the HALEU Availability Program. Above all, the most important thing is that activities in all categories are specified by relevant legislation and are actively funded.

3.2 Timelines for advanced reactor deployment process

The activities carried out by the U.S. for the deployment of ARs from 2018 to 2030 are classified using the framework and made into a timeline, and that is shown in Fig.3 [5].

What is noteworthy is that preparations for HALEU supply in the US began earlier in 2019 than the start of ARDP, which began in earnest in October 2020. The US has been concerned about its low supply of enriched uranium since the early 2010s, but no appropriate measures have been taken. However, in November 2019, DOE signed a demonstration project contract with Centrus Energy to construct a cascade through new AC-100M gas centrifuges for HALEU production. Budget support at the federal level by 2031 is expected to total $4,245 M.

Activities for the deployment of advanced nuclear reactors in the US are accelerating day by day through bipartisan agreements from the US Congress. The International Nuclear Energy Act passed in 2022, following the significantly amended Energy Act in 2020 and the Energy Infrastructure Act in 2021, seeks to reconsider US leadership in the world nuclear energy field by putting the US at the forefront of deploying advanced nuclear reactors. However, despite the active efforts of the United States, it has not been able to secure sufficient production of HALEU, and the deployment schedule, which was targeted for 2028, is being delayed after 2030.

3.3 Estimations on the HALEU demand and production

The Nuclear Energy Institute (NEI) of the United States estimated that a cumulative 125 MT of HALEU will be needed by 2026 and 700 MT of HALEU by 2030 to support US demonstration experiments.

However, this estimate includes all the requirements for a number of commercial reactors in the US under -

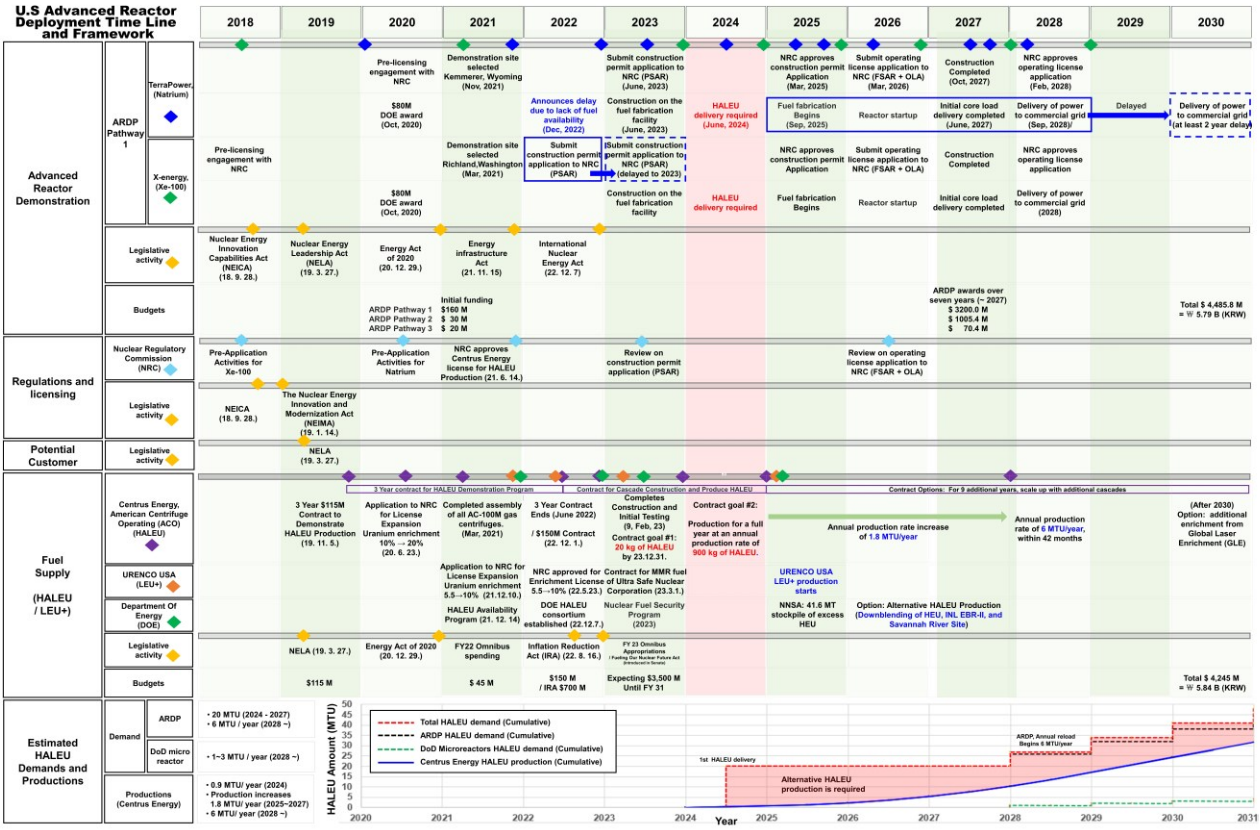

Fig.3. Timelines for advanced reactor deployment process

development. If we consider only the HALEU required for TerraPower and X-energy reactors, which corresponds to the government-led ARDP pathway 1, and the microreactor for the US Department of Defense, the cumulative HALEU requirement until 2030 is about 41 MTU (see Fig. 3 and Table I) [6].

Table I: HALEU demand and production amount (MTU)

Year	HALEU Demand (MTU) (Cumulative)			HALEU Production (Cumulative)
	DoD Micro-reactors	ARDP	Total	Centrus Energy
2020	-	-	-	-
2021	-	-	-	-
2022	-	-	-	-
2023	-	-	-	0.02
2024	-	20	20	0.92
2025	-	20	20	2.27
2026	-	20	20	5.42
2027	-	20	20	10.37
2028	1	26	27	17.12
2029	2	32	34	24.32
2030	3	38	41	31.52

About 20 MTU will be required from 2024 for fuel production of ARDP pathway 1, and since the US' HALEU production capacity can produce 20 MTU by 2029, a significant delay in the schedule of ARDP is expected. Therefore, in order to meet the US demand for HALEU, either HEU down-blending or additional HALEU production facility expansion must be urgently carried out in the US.

4. Implications on HALEU/LEU+ supply for Korean advanced reactor deployment

Analysis of the framework and timeline for the deployment of advanced nuclear reactors in the US has the following implications for the research and development of AR in Korea. The ability to supply uranium at an enrichment level of 5 to 20% is a major factor in determining the speed of demonstration experiments and commercialization of ARs. The US has been preparing to supply HALEU nuclear fuel prior to designing and demonstrating ARs through the ARDP. In addition, as an effort for preparing LEU+ production, the US NRC recently approved a license application for up to 10% uranium enrichment to URENCO USA.

Korea is currently pursuing an innovative small module nuclear reactor (i-SMR) technology development project and aims to obtain standard design approval by 2028. Currently, there are no demonstration programs for reactors using LEU+ and HALEU in Korea. However, in the near future, LEU+ or HALEU fuel will be needed to improve the performance of these reactors. Unless the issue of uranium enrichment rights is resolved diplomatically, Korea will not be able to implement a strategy to expand its production capacity like the US. This situation in Korea makes it difficult for Korea to embark on an AR development and demonstration program, while various ARs are being researched and developed around the world.

First and foremost, an action Korea can take is to build its ability to lead advanced nuclear reactor technology at a high level. And to enable the demonstration program to proceed, it is necessary to establish a strategy for stable supply of LEU+ and HALEU nuclear fuel by establishing close partnerships with enriched uranium suppliers. Afterwards, active legislative activities for AR demonstration should be followed like the US framework.

5. Conclusions

Contrary to the framework of the US, Korea does not currently have an AR demonstration program in place. It is imperative for Korea to prioritize the establishment of an AR demonstration program and to make it a legislative priority. Based on this, detailed promotion of activities in other categories will be possible.

However, even after that, there is a big problem that Korea needs to overcome. It is the problem of supplying enriched uranium for use in advanced nuclear reactors. In a situation where it is doubtful whether the US will be able to meet their demand, it is very difficult to predict that US-made HALEU can be supplied to future Korean projects. The current unstable situation over imports of enriched uranium from Russia further exacerbates the situation in Korea.

If Korea wants to build an AR without falling behind the pace of technological development, Korea must establish a long-term HALEU supply and demand strategy. Korea's financial assistance to HALEU capacity expansion efforts in the United States is one possible strategy for Korea. Bold investment support for Centrus Energy or URENCO USA can improve Korea's supply and demand conditions for enriched uranium in the future.

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