Denuclearization Study on Possible Future Options for Dismantlement and Verification of Uranium Enrichment Facility

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Abstract
Denuclearization is a process and not a single event, that requires political decision, bilateral or multilateral consultations and agreements, technical process for removal/disposal of nuclear explosive device (NED) and nuclear material, dismantlement /disablement of nuclear weapon facility and nuclear fuel cycle facility, technical process to verify denuclearization.
To improve preparedness of future denuclearization, series of study to achieve effective and efficient denuclearization have been performed in ISCN. The study includes two phases, (1) lessons learned from past denuclearization experiences and (2) possible future dismantlement and verification options.
(1) Lessons learned from past denuclearization experiences
This phase of study covered past and ongoing denuclearization efforts, such as South Africa, Libya, Iraq, 3 states of former Soviet Union (Ukraine, Kazakhstan, and Belarus), Iran and DPRK. This study was performed from April 2018 to March 2020.
(2) Possible future dismantlement and verification options
This phase of study focusses on dismantlement of three key nuclear fuel cycle facilities, uranium enrichment, nuclear reactor, reprocessing facilities and quantitative evaluation of effectiveness and efficiency of future dismantlement and verification. This study has been performed since April 2020.
As part of this (2) study, this paper focus on dismantlement and verification of potential uranium enrichment facility and potential nuclear material in the uranium enrichment facility, considering (a) peaceful use operation, (b) freeze, (c) disablement, (d) dismantlement, (e) removal from the state as potential options. Quantitative evaluation of effectiveness (irreversibility) and resources requirement including resources for verification of each option were performed and summarized in this paper.

Keywords: denuclearization, uranium enrichment, dismantlement and verification

1. Introduction
To improve preparedness of future denuclearization, series of study to achieve effective and efficient denuclearization have been performed in ISCN. As the first phase, ISCN conducted a study on "lessons learned from past denuclearization experiences" from FY 2018 to FY 2020. South Africa, Libya, Iraq, the three former Soviet Union countries (Ukraine,

Kazakhstan, and Belarus), Iran, North Korea, and Syria) were selected as case study countries. In this study, denuclearization is defined as "the abandonment of nuclear explosive devices and/or nuclear weapon program”. Following information was collected for each state: 1) history of nuclear development and denuclearization, 2) motivation for nuclear development, 3) domestic and international circumstances at the time the decision to denuclearize was made, 4) progress in nuclear development, and 5) sanctions. (4) Progress in nuclear development, (5) Effects of sanctions, (6) Incentives for denuclearization, (7) International framework for denuclearization, (8) Methods and duration of denuclearization, (9) Verifiers and methods and duration of verification and (10) Characteristics and lessons learned from denuclearization. Past denuclearization experiences were compiled and compared to enable possible future denuclearization[i].

Based on a study on "lessons learned from past denuclearization experiences" ISCN has initiated research on "possible future dismantlement and verification options". The purpose of this study is to promote future denuclearization effectively and efficiently focus on nuclear fuel cycle facilities namely, uranium enrichment, nuclear reactors, and reprocessing.

This paper focus on dismantlement and verification of potential uranium enrichment facility, considering (a) peaceful use operation, (b) freeze, (c) disablement, (d) dismantlement, (e) removal from the state as potential options. The processes required for each option were identified, and the effectiveness and efficiency of disposal and verification were compared and discussed. Quantitative evaluation of effectiveness (irreversibility) and resources requirement including resources for verification of each option were performed and summarized in this paper.

2. Gas Centrifuge Uranium Enrichment Facility and Essential Equipment

2-1 Selection of Uranium Enrichment Technology

Uranium enrichment is a technology to increase the enrichment of fissile U-235. Since it has capability to produce highly enriched uranium (HEU), which is nuclear weapon usable material (WUM), uranium enrichment facilities are essential as denuclearization targets.

NSG Part 1 Guidelines[ii] lists eight uranium enrichment technologies: (1) gas centrifuge, (2) gas diffusion, (3) aerodynamics (nozzle method), (4) electromagnetic (EMIS), (5) atomic vapor laser isotope separation (AVLIS), (6) molecular laser isotope separation (MLIS), (7) chemical (including ion exchange), and (8) plasma methods.

Of these, methods (1) through (4) above were used for commercial uranium enrichment or for HEU production of WUM, while the other methods, even if proven in principle, remained at the laboratory or engineering-scale level of research. Among the four representative methods, the gas centrifuge has a relatively high separation factor, low power consumption, and has been developed for commercial and WUM production purposes. Therefore, this study will focus on gas centrifuge uranium enrichment.

2-2 Model Gas Centrifuge Enrichment Facility

The model gas centrifuge uranium enrichment facility was developed for the study.

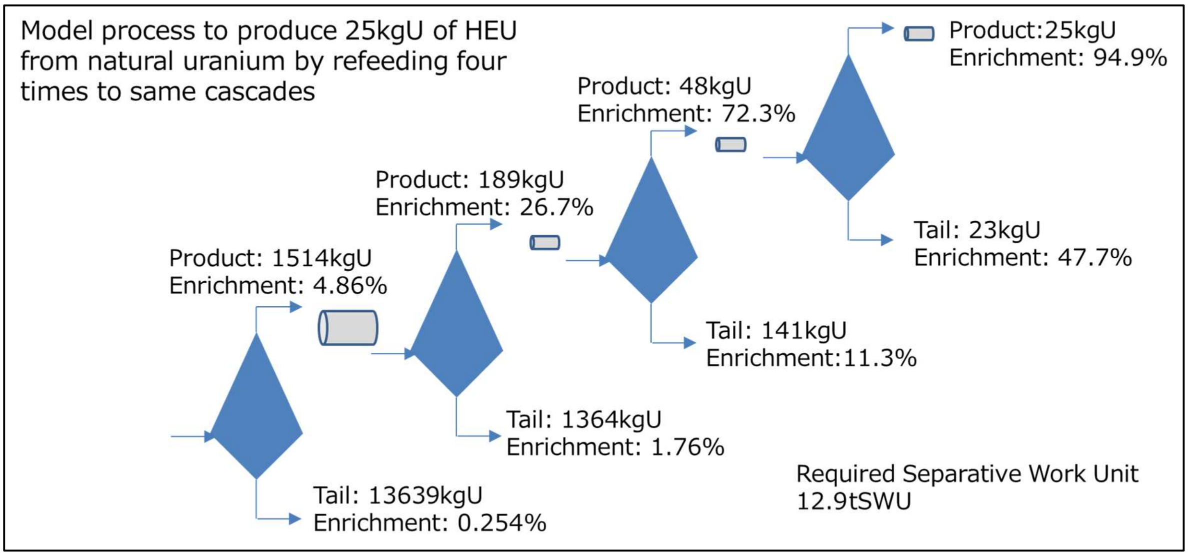

Figure 1. Model Uranium Enrichment Process

As shown in Figure 1, model facility was designed to have 12.9 tSWU/year, capable to produce 25 kg of 95% highly enriched uranium per year by refeeding product material three additional times.

The facility consists of 8,200 centrifuges (164 machines per cascade, 50 cascades, 1.6 kgSWU per machine), feed system/product and tails withdrawal systems (12 vessels, 4 vessels for 30B cylinder x 2 and 5A cylinder x 2 each for feed, products, and tail, 6 pumps,), frequency exchangers 50 sets (1 set for each cascade), 2 units of UF6 mass spectrometers.

2-3 Essential Equipment and Priority for Dismantlement

In order to effectively implement measures such as disposal in denuclearization, it is important to identify essential equipment to be disposed and to specify their priorities. Major equipment is evaluated in terms of importance and expertise and prioritized as follows;

(1) gas centrifuges
(2) frequency changers
(3) feed system/product and tails withdrawal systems
(4) UF6 mass spectrometer and ion source

3. Dismantlement and Verification of Uranium Enrichment Facilities

To implement the denuclearization of uranium enrichment facilities effectively and efficiently, the following processes for dismantling and verification were discussed.

- Verification to confirm completeness/correctness of declaration of nuclear development program
- Freezing, disablement and decommissioning of equipment, etc. to irreversibly prevent the resumption of nuclear development
- Verification after above measures

For each process, based on several assumptions, effectiveness and resources requirement of the process were evaluated quantitatively.

4. Verification to Confirm the Completeness/Correctness of nuclear program declarations

Possible activities to verify the completeness of declaration of nuclear development include the following for uranium enrichment facility;

(i) Verification of cascade design, number and specifications of centrifuges, number and specifications of frequency exchangers, (3) feed system/product and tails withdrawal systems, to confirm uranium enrichment capacity

(ii) Verify the production history of highly enriched uranium, verification of operation records showing the operation history, the number of waste cylinders and empty cylinders, the amount of UF6 in tail cylinders and the enrichment level

(iii) Verification that undeclared uranium enrichment is not taking place using visual observation, radiation monitoring, and environmental sampling.

Of these activities, activities (i) and (ii) can be carried out in one to several weeks in the presence of the Verification Implementation Agency (IAEA), if necessary. If doubts arise, a longer period is required. (iii) requires continuous implementation.

5. Potential Options for Dismantlement

The options for denuclearization of uranium enrichment facilities were evaluated, such as, continuing operation for civilian use, freezing the facility, disabling the facility, decommissioning the facility, and transferring the facility out of the country.

5-1 Civilian Use

As a result of negotiations for denuclearization, it is assumed that the facilities will not be decommissioned and will continue to operate as peaceful civilian use.

In the case of uranium enrichment facilities, conversion to civilian use is relatively easy, and if necessary, an upper limit of uranium enrichment and an upper limit of annual separation work should be set. If these necessary measures are taken in the presence of experts, it is assumed that they can be implemented in a relatively short time (within one week).

5-2 Freezing

During negotiations for denuclearization, it is necessary to freeze the facilities and ensure that no uranium enrichment work is being conducted. As a result of the negotiations, measures to freeze the facilities may be applied for a long period of time. The following measures of freezing are required;

- Stoppage of centrifuges
- Stoppage of frequency converters
- Stoppage of feedstock supply, products and depleted uranium recovery systems,
- Removal of feed, product and waste cylinders from vessels
- Stoppage of UF6 mass spectrometer and ion source

It is assumed that these necessary measures, when implemented in the presence of experts, can be carried out in a relatively short time (within a week).

5-3 Disablement

As a measure for disablement, it is important to disable high-priority equipment first. For centrifuges, three options are considered: (1) destruction of internal components such as rotors by causing distortion to the rotors through operation at a higher frequency than specified, (2) destruction by introducing air containing moisture into the high-speed rotor, loss of balance due to air inflow, and uneven loading due to solid formation on the rotor surface, and (3) destruction by making holes in the centrifuge (Table 1).

Essential equipment	Options	Irreversibility (effectiveness)
Gas centrifuge	①rotate rotor higher than the specification and destroy centrifuge.	△ Cannot confirm visually.
	②Introduce air with moisture to rotating centrifuge and destroy.	△ Same as above
	③Drill centrifuge make a hole in rotor。	◎ Can confirm visually.
Feed withdraw station	Drill and make hole in pipes and vessels and destroy airtightness. Destroy vacuum pomp by operation without oil.	◎
Frequency exchanger	Physically damage boards, cables and connectors. Splay salty water or corrosive solution.	◎
UF6 mass spectrometers /ion sources	Physically damage boards, cables and connectors.	◎

Table 1. Disablement Options and Irreversibility

-Cost Estimates for Disablement

Resources required for the centrifuge disablement.

<u>Cost and time estimates for incapacitation (options (1) and (2) to destroy the centrifuge by high frequency operation and air introduction)</u>

(Estimation of time) Assuming that local workers cooperate in the destruction work, Day 1: Confirmation of centrifuge operation status; Days 2~4: Destruction operation and frequency converter display, confirmation of destruction by sound and vibration in cascade room (8,200 machines processed in 3 days); Days 1~4: Parallel destruction of non-centrifuge equipment; Day 5: Confirmation of equipment destruction status. All work will take 5 days (1 week).

(Estimated cost) Assuming that a team of 6 experts (2 specialists, 3 technicians, and 1 communication (English) and overall supervisor) will be dispatched to the site to lead the local work team and carry out the work, the total cost of personnel, travel, lodging, and accommodation, protective equipment, dosimeters, etc. will be about 10 million yen.

<u>Cost and time estimates for incapacitation (3) Option to drill holes in the centrifuge</u>

The centrifuge is physically destroyed by drilling a hole from the outside of the casing (the entire rotating body inside is destroyed or deformed), and connectors, etc. are also destroyed as a precaution. Assuming that local workers would perform the destruction work, and assuming that the number of centrifuges that could be destroyed by one team was 100 per day, two to three teams were assumed to be working simultaneously.

(Estimation of time) Preliminary investigation and preparation: 1 week, destruction of

centrifuges: 8 weeks, destruction of equipment other than centrifuges: 1 week, post-processing and confirmation: 1 week, all work takes 11 weeks.
（As with the above option, a team of six experts would be dispatched to the site to lead a local work team to perform the work. The total cost of personnel, travel, lodging, and accommodation, protective equipment and dosimeters, and necessary tools would be approximately 70 million yen.
For any of the options, the following points should be considered when conducting the actual work;
・Securing lodging, meals, communications, and interpreters
・Establishing a medical system in case of emergency
・Arrangements (including transportation) and costs for tools and other equipment if they are in short supply
・Poor work environment (radiation exposure and contamination), if any

5-4 Decommissioning
For the decommissioning of the uranium enrichment facility, the resources required for decommissioning were evaluated using an actual example of the decommissioning plan for the Ningyo-Toge Uranium Enrichment Demonstration Plant (Ningyo-Toge DP)[iii].
The decommissioning plan approved in January 2021 states that the total estimated cost of dismantling the facility is about 5.5 billion yen and the period is about 20 years.
The facility is a relatively large facility with a separation capacity of 200 tSWU, and was in operation from 1988 to 1999, and the facility was also used for uranium enrichment of recovered uranium at a reprocessing facility.
For the facilities that are expected to be decommissioned, assuming that the safety regulations are less strict than in Japan and that they are smaller facilities, the decommissioning cost is estimated to be 1.6~2.8 billion yen and 5~10 years, based on a calculation of 1/4~1/2 of the Ningyo-toge DP.
5-6 Removal from the country
In past denuclearization cases, centrifuges and other equipment were removed from the country during the denuclearization of Libya. In this section, options for removing major equipment out of the country are discussed.
Centrifuges and high-frequency power supply units are to be removed. In particular, it is assumed that about five times longer time (20 machines/day, 1 group) is required than for option (3) (option of drilling holes in centrifuges) of decommissioning, for disconnecting piping, etc. of centrifuges, removing the main body of centrifuges, etc.
Roughly, it would take about 55 weeks, and the cost of removing the required centrifuges, etc. would be about 500 million yen, plus the cost of transportation and shipping containers, and storage.
5-7 Evaluation of Effectiveness and Irreversibility of Options for Each Measure
The effectiveness and irreversibility of each dismantlement option is evaluated in terms of the estimated period of time required to return the facilities necessary for the production of

nuclear weapons source materials to an operational status after the measures.

Assuming that the necessary raw materials could be readily procured in the state, for uranium enrichment facilities, the time required to manufacture and install each piece of equipment, etc., was assumed to be the following;

・Construction of the building (including installation of utility systems): 1 year

・Manufacture and assembly of centrifuge components: 16 months (500 machines/month)

・Manufacture of high frequency power supply: 6 months; manufacture of uranium supply and recovery equipment: 6 months

Since parallel work is also possible, the required time (irreversibility) was evaluated as follows.

・Decommissioning and removal from the country (construction of new facilities): 2 years

・Incapacitation (removal of equipment from the facility after the measure and manufacture/installation of new equipment): 2 years

・Continuation of operation/freezing (all equipment is ready for use): 0~ several weeks

Assuming that the production and installation of centrifuges is the rate-limiting factor, the effect/irreversibility of incapacitation, decommissioning, and removal from the country is evaluated to be about the same for uranium enrichment facilities. With regard to the decommissioning of facilities that are highly specialized and capable of producing centrifuge components and high-frequency power supplies, the effectiveness and irreversibility would be further increased.

6 Verification after Dismantlement Measures

The purpose methods for verification and necessary resources after implementation of each dismantlement measure were evaluated based on the experience of implementing safeguards at uranium enrichment facilities, and the results are summarized in Table 2.

Options	Verification measures	Required resource
Operation of facility for peaceful purpose	Detection of diversion and misuse. Annual PIV/DIV, few times per year to monthly inspection、LFUA、application of pipe monitor。	30-200 PDI/year （12 M-0.1 B yen /year)
Freeze	Detection of undeclared operation. Few times per year to monthly LFUA or DIV.	6-12PDI/year（3-6M yen/year)
Disablement	Detection of replacement of essential equipment. Annual inspection.	2PDI/year（1M yen/year)
Decommissioning	Not necessary	Confirmation of decommissioning
Transfer to Other State	Not necessary	Confirmation of transfer of equipment

Assuming cost of verification 1 PDI = 0.5 M yen

Table 2. Resource Required for Verification

7. Summary

With regard to uranium enrichment facilities, we quantitatively evaluated the time and resources required for dismantlement and verification for five options for gas centrifuge uranium enrichment facilities: continuing operation as civilian use, freezing the facility, decommissioning the facility, and transferring the facility out of the country, and summarized in Table 3.

Options	Effectiveness/ irreversibility	Resource required for each option	Resource required for each verification
Operation of facility for peaceful purpose	× All equipment operational	◎ Within a week	× 12M-0.1B yen /year
Freeze	× All equipment operational	◎ Within a week	× 3-6M yen/year
Disablement	○ Requires 2years	○ 1-11weeks 10-70M yen	○ 1M yen/year
Transfer to Other State	◎ Requires 2years	△ 55 weeks around 0.5B yen + shipping and storage costs	◎ No verification
Decommitioning	◎ Requires 2years	× 5-10 years 1.6-2.8B yen	◎ No verification

Table 3. Summary of evaluation of dismantlement Options

Comparing the effectiveness and efficiency of denuclearization, "disablement" is considered to be an effective option because its effectiveness is relatively high and the resources required are lower than those of "decommissioning.

The options of "civilian use" and "freezing" are less effective as options for denuclearization because the capacity of the facility will be maintained, which is extremely irreversible.

Since the weight of major components of uranium enrichment facilities is light and contamination by radioactive materials is limited, "removal from the country," as in the "Libyan model," can be considered as an option for small-scale facilities.

In addition to uranium enrichment facilities, the effectiveness and irreversibility of disposal will be further enhanced by disposing not only of uranium enrichment facilities but also of facilities that manufacture centrifuge components and facilities capable of producing high-frequency power supplies, so it is desirable to include these facilities in the disposal target.

References

[i] "Analysis on Essential Factors for Successful Denuclearization", Tazaki et al., INNM & ESARDA Joint Annual Meeting, 2021 August

[ii] NSG Part 1 Guidelines – INFCIRC/254/Rev.14/Part 1

[iii] Decommissioning Plan for the Ningyo-Toge Uranium Enrichment Demonstration Plant (October 2021 Japanese) https://www.jaea.go.jp/04/zningyo/211029-1.pdf