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Analysis on Possible North Korea's Uranium Stock by Using Open-source Information

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1. Introduction

The gas centrifuge plant in Yongbyon is the only revealed uranium enrichment plant in North Korea [1].

Yongbyon enrichment plant is believed producing only LEU below 5 percent uranium 235 for use as fuel in the LWR, as they said. But the plant could be easily converted to producing HEU for nuclear weapons [2].

In this paper, we estimated the enrichment capability of the Yongbyon plant based on the known characteristics of its centrifuges and cascades. And then we developed the four possible uranium enrichment scenarios, to examine the future options that North Korea may use to enhance its enrichment capability. Finally, we suggested several key measures to stop North Korea from pursing its nuclear ambitions.

2. Analysis

Lack of the available information on the detailed specification of the centrifuges and cascades, and the operation parameters of the Yongbyon plant, there remains uncertainties associated with the estimate.

2.1 Enrichment Capability

Yongbyon enrichment plant began operation in Nov. 2010. Six cascades (in total about 2,000 centrifuges) have been installed in two units. Each cascade consists of 334 centrifuges. The centrifuges are believed to be based on the P-2 model. More detailed Information on the estimated design characteristics of its centrifuges is shown in Table I.

Table I: Estimated design characteristics of centrifuges deployed in the Yongbyon enrichment plant

Estimated Characteristics				**Ref.**
Centrifuge type			P-2	[1,2]
Operating temperature (T)			320 K	[3]
Operating pressure (P)			100 torr	[3]
Process gas	*Type*		UF6	[1~4]
	Molecular weight (M)		352 g/mole	[3,4]
	Mass Difference (ΔM)		3 g/mole	[3,4]
	Density(ρ) x coeff. of self diffusion(D)		2.2E-05 kg/(m s)	[3]
Rotor	*Material*		Maraging steel	[1~3]
	Velocity (V)		485 m/s	[3]
	Radius (a)		7.5 cm	[1~3]
	Length (Z)		1 m	[2,3]
Separative power	*Maximum Theoretical* (δU_{max})		**13 kg-SWU/yr**	Eqn(1)
	Actual	*Upper bound* (δU_{actual_upper})	**4.5 kg-SWU/yr**	Eqn(2)
		LowerBound (δU_{actual_lower})	**1.8 kg-SWU/yr**	Eqn(3)

North Korea has stated that its total enrichment capability is 8,000 SWU/year. With 2,000 centrifuges, the centrifuge enrichment capability would be 4 SWU/yr [1, 2]. Centrifuge enrichment capability can be achieved easily by following equations. According to our calculations, this average value for the centrifuge is credible.

$$\delta U_{max} = \rho D\left(\frac{\pi Z}{2}\right)\cdot\left(\frac{\Delta M}{2RT}\right)^2 (V)^4 \quad (1)$$

$$\delta U_{actual\_upper} = \delta U_{max}\cdot e_I \cdot e_c \cdot e_F \quad (2)$$

$$\delta U_{actual\_lower} = \delta U_{max}\cdot e_I \cdot e_c \cdot e_F \cdot e_E \quad (3)$$

Where,

e_I (Ideality efficiency) = 0.81

e_c (Circulation efficiency) = $\frac{m^2}{1+m^2}$ = 0.92(0.9~0.94)

(m is typically optimized around 3 to 4)

e_F (Flow Profile efficiency) = $\frac{14.4RT}{MV^2}$ = 0.46

e_E (Experimental Efficiency)

= 0.4(0.35~0.45) , for new designs

= 0.55(0.5~0.6), for established production machines

Estimated LEU production capability of the Yongbyon plant is shown in Table II. To figure out its WGU (Weapons Grade Uranium; 90% HEU) production capability, we considered the step wised WGU production cascade design that Khan sold to Libya [2]. The brief explanations about the cascade design are shown in Table III.

Table II: Estimated LEU production capability of the Yongbyon plant

Estimated Characteristics		**Ref.**
Concentration of Stream (T:Tails, F:Feed, P:Product)	T: 0.27% F:0.71% P: 3.5%(avg)	[1]

Centrifuge Separation Capacity	*Upper bound*	4.5 kg-SWU/yr/centrifuge	
	Lower Bound	1.8 kg-SWU/yr/centrifuge	
No. of installed centrifuges		2,064	[5]
No. of operating centrifuges		1,968	[5]
Annual Enrichment Capacity	*Upper bound*	8,856 kg-SWU/yr	
	Lower Bound	6,376 kg-SWU/yr	
Annual output		**1.4 ~ 1.9 ton-U/year**	
Accumulated product (as of the end of Oct. 2012)		**2.8 ~ 3.8 ton-U**	
Accumulated feed (as of the end of Oct. 2012)		**20~28 ton-U**	

Table III: Reference WGU production cascade design

	No. centrifuges	**Concentration of Stream (F:Feed, P:Product)**
1 step	*3,936*	F:0.71%, P:3.5%
2 step	*1,312*	F:3.5%, P:20%
3 step	*546*	F:20%, P:60%
4 step	*128*	F:60%, P:90%
Total No. of centrifuges		5,832
Annual output		100 kg-U/year
Annual output per 2,000 centrifuges	*Upper bound*	**34 kg-U/year**
	Lower Bound	**8.3 kg-U/year**

2.2 Possible Uranium Stock

Although, it is possible that North Korea has already produced or will produce WGU in secret centrifuge plants. But if we include these factors, the uncertainly will grow too much. Therefore, the following four scenarios are focusing on the only Yongbyon plant, to examine the future options that North Korea may use to enhance its enrichment capability.

Scenario 1 is based on North Korea's declaration. Yongbyon enrichment plant is producing only LEU below 5 percent uranium 235 for use as fuel in the LWR.

The reactor will be fueled with 3.5 % uranium dioxide fuel, and a full fuel load is 4 ton-U(18,460 kg-SWU). After Starting operation, every year, about 1~1.4 ton-U (1/4~1/3 of total fuel load; 4,615~ 6,150 kg-SWU) must be required to maintain the LWR. Therefore, with the rest of enrichment capability (230~ 4,240 kg-SWU/year) and excess 3.5% LEU, North Korea would increase the enrichment level. Like Iran, in order to produce fuel for its research reactor, IRT-2000, North Korea is likely to produce 19.75% LEU. Scenario 2 and 3 are considering these factors.

As shown in scenario 4, North Korea could also use the Yongbyon plant to make weapon-grade uranium. It could convert some of the cascades to higher enrichment production or first make sufficient LEU and then enrich stepwise to WGU in the same cascades [2].

Table IV: Four Uranium enrichment Scenarios at the Yongbyon plant

Scenario		**Probability**	**Annual output [kg-U/year]**		
			3.5 % LEU	**19.75% LEU**	**90% HEU**
Scenario 1	Production of 3.5% LEU	High for a while, Medium after starting operation of LWR	1,400~1,900	0	0
Scenario 2	Production of both 3.5% and 19.75% LEU	Low for a while, Medium after starting operation of LWR	1,000~1,400	5.8~107 (F:0.71%) or 28~519 (F:3.5%)	0
Scenario 3	Production of 19.75 % LEU	Low	0	160~224 (F:0.71%) or 780~1085 (F:3.5%)	0
Scenario 4	Production of 90 % HEU	Very Low	0	0	8.3~ 34

3. Conclusions

During the 3.5 years of standoff over its nuclear program, North Korea has steadily strengthened its nuclear capabilities. Therefore, halting the operation of Yongbyon enrichment plant, immediately starting the IAEA monitoring activities at the plant remains the first priority for negotiators.

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