SCIENCE & GLOBAL SECURITY
2019, VOL. 27, NOS. 2–3, 113–123
https://doi.org/10.1080/08929882.2019.1657608

Analysis of the DPRK's Nuclear Weapons Capabilities by Estimating Its Highly Enriched Uranium Stockpile and Natural Uranium Reserves

Sherzod R. Kurbanbekov[a], Seung Min Woo[a], and Sunil S. Chirayath[a,b]

[a]Center for Nuclear Security Science and Policy Initiatives, Texas A&M University, College Station, TX, USA; [b]Department of Nuclear Engineering, Texas A&M University, College Station, TX, USA

ABSTRACT
There is a shortage of reliable information on the highly enriched uranium (HEU) stockpile, production capabilities, and natural uranium reserves of the Democratic People's Republic of Korea (DPRK or North Korea). It is, however, possible to estimate DPRK's nuclear material reserves using the data in the open literature and considering various scenarios. Based on our literature survey and analysis we are projecting DPRK's natural uranium reserves and their production capabilities of weapons-grade HEU. We also report the uncertainties associated with DPRK's uranium enrichment capabilities due to the differences in estimates provided in the literature. Our analysis shows that given the range of the estimates of DPRK's natural uranium ore reserves, its nuclear weapons program is unlikely to be constrained by uranium resources, provided they have the required mining and milling capacities.

ARTICLE HISTORY
Received 29 April 2019
Accepted 4 August 2019

Introduction

An estimate of natural uranium stockpile is important for understanding the capability of a state to produce fissile materials for military as well as civilian purposes. Unfortunately, in the case of the Democratic People's Republic of Korea (DPRK or North Korea), there is no official information on the production and consumption of uranium. The estimate of the size of uranium reserves in North Korea, however, could be done indirectly, based on the openly available information, even though such an estimate might not be highly accurate.

The DPRK unilaterally withdrew from the Treaty on the Nonproliferation of Nuclear Weapons (NPT) in January 2003 and is not a party to the Comprehensive Nuclear-Test Ban Treaty (CTBT).[1] The DPRK has conducted six nuclear tests since 2006, demonstrating increasingly advancing capabilities

CONTACT Sherzod R. Kurbanbekov sherzod@tamu.edu Center for Nuclear Security Science and Policy Initiatives, Texas A&M University, College Station, TX, 77843, USA.
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of its nuclear weapon program. The DPRK program caused serious concern in the international community and was condemned in several United Nations Security Council resolutions.[2] The DPRK's nuclear weapons potential remains in the focus of attention of the international community, but there has been little progress in constraining or eliminating the program. Despite the efforts made by the United States and South Korea through diplomatic channels, including the Singapore and Hanoi summit meeting between the U.S. President, Donald Trump, and the DPRK Chairman, Kim Jong-un, it is not clear whether DPRK would be willing to eliminate its nuclear weapon capability.[3]

While the DPRK program remains intact, it is important to know what the factors are that may constrain the program. In particular, how large are North Korea's natural uranium reserves? What amount of uranium mining and milling capacities does North Korea possess? What do we know about the uranium ore quality? This paper attempts to provide an estimate based on a parametric study with input data from open sources.

An estimate of the natural uranium reserves and potential highly enriched uranium (HEU) stockpile of the DPRK

A number of studies have been conducted by various researchers to estimate DPRK's nuclear weapons arsenal as well as their capabilities in producing nuclear weapons–useable fissile material. Based on the information available on the DPRK's nuclear facilities, it can be envisaged that they have plutonium- and uranium-based nuclear weapons.[4] It should be noted that the DPRK has a MAGNOX-type natural uranium–fueled, graphite-moderated, gas-cooled reactor that was put into operation in Yongbyon in 1986.[5] The 5 MWe reactor was able to produce about 6 kg of plutonium annually.[6] Based on the estimate of the operating histories of the reactor and the associated radiochemistry laboratories, the size of the plutonium stockpile in 2007 was estimated to be between 46 and 64 kg.[7] Between 28 and 50 kg of that was separated and available for use in nuclear weapons.[8] An updated assessment by Albright in 2015 estimated that the DPRK has between 30 and 34 kg of usable plutonium, a decrease caused by the nuclear tests of 25 May 2009 and 12 February 2013.[9]

Since the late 1990s, experts have stated that the DPRK started uranium enrichment studies. Later, it was disclosed that Pyongyang received about two dozen centrifuges from the A. Q. Khan network.[10] It is likely that the DPRK was able to duplicate or modify these centrifuges and build up its own independent HEU production capability.

In November 2010, after the visit of the U.S. team to the Yongbyon Nuclear Center, Dr. Siegfried S. Hecker (member of the visiting U.S. team) wrote that at Yongbyon fuel fabrication site they were shown a new facility that contained a recently completed modern, small industrial-scale uranium enrichment facility with about 2000 centrifuges. The DPRK claimed that the centrifuges were producing low enriched uranium (LEU) for the fuel of the new reactor.[11] According to Hecker's report, the enrichment capacity was 8000 kg-SWU/y and average uranium enrichment level was 3.5 wt% and the tails are 0.27 wt%. The facility was intended to supply LEU for a 100-MWt (about 25–30 MWe) experimental light-water reactor at the Yongbyon Nuclear Complex. According to Hecker, the plant can annually produce 2 tons of LEU, or up to 40 kg HEU if the cascades are reconfigured (assuming 90% enrichment). This estimate is obtained by assuming 2000 number of P2-type centrifuges each with a 4 kg-SWU/y capacity, i.e., 8000 kg-SWU/y. Other estimates suggest that P2-type centrifuges can have a somewhat larger capacity, from 4 to 6 kg-SWU/y.[12] There is currently no reliable information whether uranium enrichment activities had been carried out at the Yongbyon Nuclear Complex for military purposes, but the possibility of such activities cannot be ruled out. The stockpile of HEU was estimated and reported in 2015 based on two different scenarios.[13] The first scenario assumed operation of two centrifuge plants; the first plant operating with the capacity of 2000 to 3000 P2-type centrifuges between 2005 and 2010 to produce HEU and the second plant with 2000 P2-type centrifuges that produced LEU until 2014, which may have been reconfigured to produce HEU after 2014. The second scenario assumed the DPRK operating 2000 P2-type centrifuges between 2010 and 2011 to produce LEU and reconfiguring them to produce HEU after that. The median value for the first scenario is 240 kg of HEU and for the second scenario is 100 kg of HEU.[14] According to a report by the Center for International Security and Cooperation (2016 CISAC Report), by 2015 North Korea has around 6000 centrifuge-enrichment complex divided into a base facility of 4000 centrifuges in Yongbyon producing LEU and a clandestine "topping plant" of 2000 centrifuges located elsewhere.[15] Based on this information, approximately 100 kg of HEU could have been produced per year. The same report estimates that by 2017, an additional 2000 centrifuges could be clandestinely installed. With this addition, the total expected yield of HEU could be between 130 and 150 kg per year.

Even greater concerns of the international community were caused by the satellite imagery data in 2013 indicating twofold increase of the roof area over the uranium enrichment facility at the Yongbyon nuclear complex compared to the date in 2010.[16] This suggests that the DPRK could have at least doubled its uranium enrichment capacity from 2000 centrifuges to 4000 centrifuges with the potential of producing 100 kg of HEU per year, which is equivalent to four nuclear weapons annually, if a capacity of 5 kg-SWU/y per centrifuge is assumed.[17] This aspect largely confirms the estimates reported earlier in the 2016 CISAC report. Similar estimates were provided by Olli Heinonen, former director of the International Atomic Energy Agency's (IAEA) Department of Safeguards, who based his estimate on the analysis of the DPRK's purchases of relevant equipment and components. Heinonen concluded that the DPRK is likely seeking to produce additional 5000 centrifuges and obtain spare parts for the repair of 900 centrifuges.[18] Albright's research article published in 2018 reported that the DPRK may have another secret uranium enrichment site at Kangsong and suggested the facility may be a gas centrifuge plant with up to 6000 to 12,000 P2-type centrifuges.[19] A February 2019 report by Hecker stated that the DPRK could be possessing 8000 P2-type centrifuges.[20]

The number of centrifuges assumed by various researchers as discussed above is summarized in Table 1.

In addition, some information about the natural uranium reserves in the DPRK is available. One estimate suggests that the DPRK has industrial reserves of uranium ore estimated at 300,000 metric tons that is sufficient to develop national nuclear power and boost nuclear arsenal.[21] One metric ton of DPRK's uranium ore contains an average of about one kilogram of natural uranium assuming an ore quality of 1000 parts per million (ppm).[22] Therefore, about 50,000 metric tons of the ore had to be extracted and processed in order to obtain 50 tons of the natural uranium needed for the initial fuel load for the 5 MWe Yongbyon reactor.[23] The Soviet Union conducted a series of exploration tasks on uranium ores in the DPRK from 1947 to 1950. It reportedly found that DPRK has up to 26 million metric tons of uranium ore, of which about 4 million metric tons are suitable for industrial development.[24] Various other sources in the literature also report that the DPRK's natural uranium ore reserves is 26 million tons.[25] Analysis of North Korea's Nuclear Weapons program by the International Institute of Strategic Studies in 2006 reported that about 30,000 tons of uranium ore per year was processed, which also suggests the amount of natural uranium ore reserve in North Korea is much higher than the 300,000 metric tons mentioned at the beginning of this

Table 1. Estimated number of centrifuges in DPRK. SWU estimate assumes the range of 4 to 6 kg-SWU/y per centrifuge.

Reference	Number of centrifuges	kg-SWU/y
Hecker (2010)	2000	8000–10,000
Heinonen (2015)	5900	23,600–35,400
Braun et al. (2016)	6000	24,000–30,0000
Albright (2018)	10,000–16,000	40,000–96,000
Hecker (2019)	8000	32,000–48,0000

paragraph.[26] Hence, there is every reason to believe that DPRK's natural uranium reserve is closer to 4 million tons or more.

Estimates of the projected size of the DPRK nuclear arsenal vary. Some experts believe that for effective deterrence DPRK needs to own about 80 to 100 nuclear weapons, which can take about 5 to 10 years to produce. Others believe that the DPRK just needs between 40 and 50 nuclear weapons to ensure their credible deterrence. There are some data indicating that the DPRK possesses 20 to 40 nuclear weapons.[27] Recent U.S. analysis estimated that the DPRK has 60 nuclear weapons.[28] The 2018 Center for International Security and Cooperation (CISAC) Report estimate puts the number of weapons in DPRK's arsenal between 35 and 37.[29] Most estimates suggest that DPRK seeks a stockpile of at least 40 to 50 nuclear weapons. This means that it needs an additional source of weapon-grade nuclear material other than that supplied by the Yongbyon reactor. It is not known whether DPRK has built uranium-based nuclear weapons. However, by all indications the DPRK leadership made uranium enrichment a higher priority than its plutonium production program.

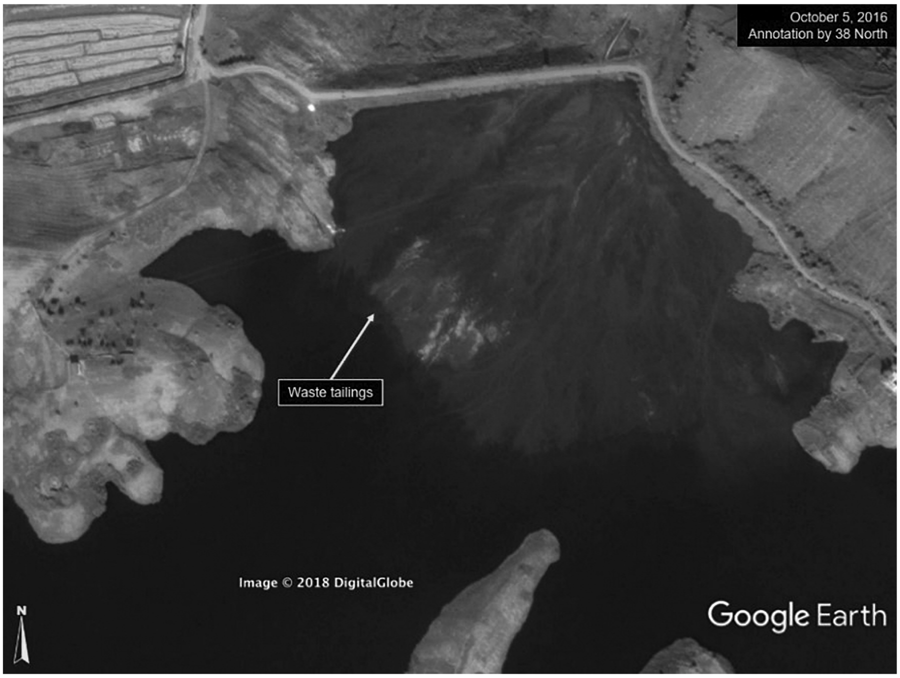
Estimating DPRK's HEU stockpile and monitoring its change is therefore important, as it will determine the size of its nuclear arsenal. Researchers have approached this from different directions. An analysis of commercial satellite imagery of the Pyongsan Uranium Concentrate Pilot Plant, one of the DPRK's two largest declared uranium ore concentrate facilities, suggests that the plant has continued to expand. Figure 1 shows a significant increase in waste tailings discharged into the river from 2016 to 2018. This also indicates that the DPRK is expanding its uranium production probably for the purposes of producing nuclear weapons.[30] This paper attempts to analyze the HEU stockpile in the DPRK considering parameters of uranium enrichment process and estimated reserves of natural uranium.

Basic calculations of estimated HEU production

Production of HEU in DPRK is based on the gaseous centrifuge technology. Natural uranium contains 0.711% of uranium-235 and more than 99% of uranium-238, with a negligible amount of uranium-234. Enriched uranium that is used in nuclear weapons is typically 90% or more of uranium-235.

To determine the expected stock of HEU in the DPRK, we will use the uranium enrichment cascade theory. In the enrichment process there are essentially three types of material flow, i.e., of the feed, tails, and product. A mass balance at the enrichment plant includes the mass of the feed (F), product (P), and tails (W) streams and the concentration of uranium-235 isotope (x_F, x_P, x_W) in each stream. The feed concentration, x_F of uranium-235 is the natural abundance of uranium while the product concentration,

(A)



(B)

Figure 1. Waste tailings discharged into the river from 2016 to 2018. (A) Satellite image taken in 2016. (B) Satellite image taken in 2018. Reproduced with Permission from Airbus Defense & Space and 38 North, along with Pleiades © CNES 2019 (see 32 in Notes and Reference section).

x_P, is established as the desired uranium-235 enrichment. The concentration of uranium-235 in tails, x_W, is usually kept in the range of 0.25 to 0.35%.[31]

Using these parameters, the SWU calculator can be used to assess the HEU enrichment capabilities including SWU capacity of the DPRK by considering the variations in these input parameters reported in the literature as discussed above.[32]

Analysis of the results

We estimated DPRK's HEU stockpile by taking into account the range of data on the number of centrifuges and the capacity of individual centrifuges discussed earlier. Combined, these estimates produce the range of the SWU capacity between about 30,000 and 100,000 kg-SWU/y. The variations in natural uranium reserves, uranium ore quality, and tails assay are considered in our analysis as well. Table 2 provides all results. Some key results from the table are considered below. In this study, the SWU capacity varied from 30,000 to 100,000 kg-SWU/y with a constant product enriched to 90% of uranium-235. For the most representative data on the DPRK's HEU capabilities, we considered tails assay in the range from 0.25% to 0.35%. Assuming the SWU capacity of 30,000 kg-SWU/y, the DPRK can produce 145 and 167 kg of 90% HEU with tails assay of 0.25% and 0.35%, respectively. With the SWU capacity of 100,000 kg-SWU/y, DPRK can produce between 484 kg and 557 kg of HEU with tails assay at 0.25% and 0.35%, respectively. The natural uranium feed required to produce HEU will vary from 28,000 kg to 135,000 kg. This should be compared to the estimated 4,000,000 kg of natural uranium reserve available to DPRK if one assumes a reserve of 4 million metric tons of uranium ore with about 1000 ppm concentration of uranium.[33]

As described earlier, estimates suggest a maximum of 60 nuclear weapons in the DPRK arsenal as of 2018. About 10 use plutonium (average 4–6 kg plutonium per weapon assumed). This means that about 1250 kg of HEU should have been produced to make 50 HEU-based weapons.[34] If one

Table 2. Assessment of HEU production and feed natural uranium consumption for variations of SWU capacity and tails enrichment.

Total SWU Capacity (kg-SWU/y)	Uranium enrichment in product [wt %]	Uranium enrichment in tails [wt %]					
		0.25		0.3		0.35	
		Product (kg/y)	Feed (kg/y)	Product (kg/y)	Feed (kg/y)	Product (kg/y)	Feed (kg/y)
30,000	90	145	27,739	157	33,445	167	40,513
50,000	90	242	46,232	261	55,741	279	67,521
70,000	90	339	64,385	365	78,038	390	94,539
80,000	90	387	73,971	418	89,186	446	108,033
100,000	90	484	92,463	522	111,482	557	135,042

assumes that this material was produced between 2010 and 2018 with the enrichment complex operation at the total capacity of 30,000 kg-SWU/y and with 0.25% tails assay, this would have consumed about 236,000 kg of natural uranium. In addition, about 100,000 kg of natural uranium have been used to produce plutonium for the six tests and for the estimated 10 plutonium weapons in the current arsenal. Based on a comprehensive literature survey of older and recent material, there is every reason to believe that the DPRK possess at least 4 million tons of natural uranium ore reserve and hence can produce as many as 700 HEU-based nuclear weapons. In practical terms, this means that the DPRK nuclear program is not constrained by natural uranium resources.

Conclusion

The study presents an estimate of DPRK's weapons-grade HEU production potential by considering the variations in uranium enrichment parameters reported in the literature. Even if one assumes the SWU capacity at the lower end of the existing estimates (30,000 kg-SWU/y), it is enough to produce 145 kg of 90% HEU per year with tails assay of 0.25% and 167 kg of HEU with tails assay of 0.35%. The respective natural uranium feed requirement is found to be 28,000 to 40,000 kg per year. This is equivalent to the production potential of six uranium weapons per year. The worst case scenario is if the DPRK has the SWU capacity of about 100,000 kg-SWU/y, which is at the higher end of the estimates reported in the literature. In this case, DPRK can produce up to 20 weapons a year with a natural feed requirement of only 135,000 kg a year. Most of the literature suggests that North Korea has at least 4 million tons of natural uranium ore reserve for industrial development, and hence total natural uranium feed available is 4,000,000 kg (assuming 1000 ppm ore quality). This means that the DPRK program is not constrained by the availability of natural uranium. There is sufficient mineable uranium ore in the DPRK to produce as large a weapon stockpile the DPRK regime might conceivably want or need, provided there is the required uranium mining and milling capacity.

Acknowledgment

This work is supported by the Stanton Foundation through their Nuclear Security Fellows Program of 2018-2019.

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