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Current Estimate of North Korea's Plutonium, HEU Stocks and Nuclear Arsenal

Introduction and Summary

North Korea has adopted a policy of expanding its nuclear weapon arsenal as fast as it possibly can. All current nuclear weapons states, including North Korea, rely on both plutonium and highly enriched uranium (HEU) to produce their nuclear weapons. In order to estimate how many nuclear weapons North Korea might have, analysts have attempted to estimate how much plutonium and HEU North Korea possesses. However, many past estimates are already three years old and given the continuing North Korean production of plutonium and HEU, a more up to date estimate is needed to provide a better view of the seriousness of the current North Korean nuclear weapon threat.

Estimating North Korea's plutonium stocks is relatively easy since it only has one plutonium production reactor and the main characteristics of this reactor are known. However, many of the past estimates make assumptions which unrealistically minimize the North Korean stockpile of plutonium. This paper will make more realistic assumptions which increases somewhat the estimate of North Korea's plutonium stocks.

Estimating North Korea's HEU stocks is more difficult since it must be based on the number of North Korean enrichment plants, the number of centrifuges in each plant and the enrichment efficiency (separative work output) of each centrifuge.[2] None of these quantities are well-known. A lower bound on North Korea's HEU stockpile can be based on North Korea's known centrifuge enrichment facilities. To place an upper bound on the HEU stocks, this paper uses the constraint of North Korea's natural uranium supplies.

Though prior estimates by other analysts of North Korea's nuclear arsenal recognized that North Korea may be producing some tritium, which is an essential ingredient for the production of boosted nuclear weapons, none of these estimates attempted to quantify possible North Korean tritium stocks. In contrast, this paper has estimated how much tritium North Korea might have, based on the capabilities of its plutonium production reactor and its natural uranium mining capability.

This paper estimates that North Korea's nuclear material stockpiles at the end of 2023 are 85 kilograms of plutonium, 1,000 to 1,900 kilograms of HEU and little or no tritium. If converted into the number of weapons, assuming 5 kilograms of plutonium per weapon and 20 kilograms of HEU per weapon, then North Korea would have an estimated 67 to 112 weapons. Despite this large uncertainty range, it is clear that North Korea possesses a sizable nuclear arsenal. Based on

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[1] This paper is the product of the author's personal research and the analysis and views contained in it are solely his responsibility. Though the author is also a part-time adjunct staff member at the RAND Corporation, this paper is not related to any RAND project and therefore RAND should not be mentioned in relation to this paper. I can be reached at GregJones@proliferationmatters.com

[2] The enrichment capacity of uranium enrichment plants is measured by separative work units (SWU). There is no simple definition of what a SWU is.

current capabilities, North Korea's weapons stockpile will grow at the rate of 6 to 11 weapons per year.

In the future, North Korea's nuclear weapons stockpile could grow at a significantly faster rate. North Korea could expand its clandestine uranium enrichment capability and/or begin producing substantial amounts of plutonium from the Experimental Light Water Reactor (ELWR). A major wild card is Russia. Given NATO's support of Ukraine in its conflict with Russia, Russia might want to aid North Korea's nuclear program in order to distract the U.S. from Eastern Europe. This aid could take the form of natural uranium supplies, nuclear weapons design information or even significant amounts of tritium.

Plutonium

Current plutonium stocks

Plutonium production reactors are generally fueled by natural uranium. As this fuel is irradiated, plutonium is produced. After some time, the uranium is discharged from the reactor and then chemically processed (reprocessed) to extract the plutonium. The discharged fuel is characterized by its burnup, i.e. the amount of power that the fuel produced per unit weight. The burnup is stated in terms of megawatt-days per metric ton (MWD/MT). For a given reactor design and fuel burnup, the number of grams of plutonium per metric ton of fuel can be approximated. (See Appendix)

For a plutonium production reactor, a key parameter is its thermal power level, which in the case of North Korea's reactor at Yongbyon is 25 MWt.[3] When a refueling takes place at the North Korean reactor, apparently all of the core is replaced at the same time. The average burnup of the fuel is then the power level of the reactor, times the number of days that is has operated between refuelings, divided by the amount of fuel in the reactor which is known to be 50 metric tons. In practice the average burnup of the discharged fuel from this reactor has been determined by either International Atomic Energy Agency (IAEA) inspections, North Korean statements or satellite observations of the reactor's operation.

Table 1 shows my estimate of how much plutonium North Korea may have produced in total. The cycle numbers, dates of reactor operation and dates of reprocessing are provided by the IAEA.[4] The burnup for the first cycle is the average of the burnup distribution of the discharged fuel as determined by the IAEA.[5] The burnup for the second cycle is based on a North Korean

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[3] This reactor can produce 5 megawatts of electrical energy and in the literature is often referred to as the "5 MWe" reactor. However, producing plutonium is the main purpose of this reactor and its plutonium production is determined by its 25 megawatt thermal energy output (25 MWt) and not its 5 megawatt electrical output.

[4] "Application of Safeguards in the Democratic People's Republic of Korea," GOV2022/40-GC(66)/16, International Atomic Energy Agency, September 7, 2022, pp. 9-11. https://www.iaea.org/sites/default/files/gc/gc66-16.pdf

[5] "ISIS Course: Introduction to Reactors and Fuel Cycle: Small Yongbyon Nuclear Reactor," Institute for Science and International Security, October 16, 2014. https://isis-online.org/uploads/conferences/audio-video/Yongbyon_reactor_and_fuel_cycle_october_16_2014_-_3-2.pdf

statement to Siegfried Hecker in 2006.[6] Note the burnup for the second cycle is consistent with the reactor operating for about 300 days per year, i.e. a capacity factor of 82%. I have assumed the same reactor capacity factor for cycles 3, 4 and 5. Due to the uncertainties involved, I have rounded my plutonium production estimates to the nearest kilogram.

Table 1

Estimate of the Total Plutonium Production at North Korea's Yongbyon 25 MWt Reactor

Cycle Number	Dates of Operation	Dates of Reprocessing	Average Fuel Burnup (MWD/MT)	Plutonium Recovered (Kilograms)
0	1985-1989	3/90-5/90	?	10
1	1985-1994	2003	635	28
2	1/03-4/05	6/05-10/05	330	15
3	6/05-7/07	4/09-8/09	315	14
4	8/13-10/15	2/16-6/16	325	15
5	12/15-12/18	2/21-7/21	435	20
6	7/21-			
Total				102
Total minus processing losses and plutonium consumed in nuclear tests				85

Table 1 also contains an entry for a cycle 0, which is not included in the IAEA's accounting of the Yongbyon reactor's operating history. In 1992 when the IAEA first inspected the 25 MWt Yongbyon reactor, North Korea declared that it had previously discharged a small amount of fuel and recovered 100 grams of plutonium. The IAEA found discrepancies in North Korean statements and suspected North Korea had separated more plutonium than it had declared. When the IAEA tried to resolve these discrepancies, North Korea frustrated its efforts.[7] These events have raised the concern that a partial refueling of a significant portion of the core may have taken place before cycle 1. If so, this refueling could have provided North Korea with a significant amount of plutonium. For example, in 1994, David Albright of the Institute for Science and

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[6] Chaim Braun, Siegfried Hecker, Chris Lawrence, and Panos Papadiamantis, "North Korean Nuclear Facilities After the Agreed Framework," Center for International Security and Cooperation, Stanford University, May 27, 2016, p. 42. https://fsi.stanford.edu/publication/north-korean-nuclear-facilities-after-agreed-framework

[7] For example, when the 25 MWt reactor at Yongbyon was refueled in 1994, the IAEA wanted to measure the burnup of fuel elements taken from different parts of the reactor to see if there had been any prior partial refueling of the reactor. However, North Korea would not allow the IAEA access to the fuel as it was being discharged and jumbled the fuel in the spent fuel pond, so that such analysis could not be done.

International Security estimated that North Korea could have recovered 7 to 14 kilograms of plutonium from this cycle 0 refueling.[8]

Over time, however, Albright has tended to downplay this possibility and in 2015 said, "Absent more information, in this report, we are not including this possible undeclared inventory of separated plutonium."[9] Similarly, Braun et. al. cited above, give an estimate of "Less than 2 kg, possibly < 100g."[10] However, since the reactor operated for at least three years before the 1989 refueling, Albright's original estimate of 7 to 14 kilograms of plutonium is reasonable. As a result, I have used a midrange estimate of 10 kilograms as the amount of plutonium North Korea recovered from cycle 0.

After calculating how much plutonium North Korea might have produced, sources then calculate how much plutonium it has today net processing losses and consumption in nuclear tests. Albright reports that the U.S. Joint Atomic Energy Intelligence Committee in 1994 estimated processing losses of 20%.[11] A 2021 paper by de Lanversin & Kutt also estimated 20% processing losses, broken down as 10% reprocessing loss and 10% metal fabrication loss.[12]

However, given that the plutonium is more valuable than gold, such processing losses seem most unlikely. Data from actual processing losses experienced by other countries confirms this view. North Korea uses the U.S. developed PUREX process for the reprocessing of its spent fuel from the 25 MWt plutonium production reactor at Yongbyon. The U.S. used the PUREX process to recover plutonium from its plutonium production reactors at Hanford. The U.S. found that the amount of plutonium lost and winding up in the waste was only 0.2%, not 10%.[13] Similarly, I calculated that in 1945 U.S. metal fabrication losses could not have been more than 3%.[14] Indeed, Albright has reported that for the South African nuclear weapon program, metal

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[8] David Albright, "North Korean Plutonium Production," *Science & Global Security*, Volume 5, 1994, p. 82. https://scienceandglobalsecurity.org/archive/sgs05albright.pdf

[9] David Albright, "North Korean Plutonium and Weapon-Grade Uranium Inventories," *Institute for Science and International Security*, January 8, 2015 (revised October 7, 2015), p. 6. https://isis-online.org/uploads/isis-reports/documents/North_Korean_Fissile_Material_Stocks_Jan_30_2015_revised_Oct_5_2015-Final.pdf

[10] Chaim Braun, Siegfried Hecker, Chris Lawrence, and Panos Papadiamantis, "North Korean Nuclear Facilities After the Agreed Framework," Center for International Security and Cooperation, Stanford University, May 27, 2016, p. 42. https://fsi.stanford.edu/publication/north-korean-nuclear-facilities-after-agreed-framework

[11] David Albright and Paul Brannan, "The North Korean Plutonium Stock, February 2007," *Institute for Science and International Security*, February 20, 2007, p. 2. https://www.isis-online.org/publications/dprk/DPRKplutoniumFEB.pdf

[12] Julien de Troullioud de Lanversin & Moritz Kutt, "Verifying North Korea's Plutonium Production with Nuclear Archaeology," *Science & Global Security*, Vol. 29, No. 3, 2021, p. 149. https://scienceandglobalsecurity.org/archive/sgs29jdtdl.pdf

[13] CH Delegard and SA Jones, "Chemical Disposition of Plutonium in Hanford Site Tank Wastes," *Pacific Northwest National Laboratory*, PNNL-23468 Rev 1, May 2015, p. 52. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23468Rev1.pdf

[14] Gregory S. Jones, "Fissile Material Conversion Times, Wastage and Significant Quantities: Lessons from the Manhattan Project," December 16, 2015, p. 11. https://nebula.wsimg.com/d3cd819efec4dd9537d29075dfff524a?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1

fabrication losses of its HEU stocks were only 1.3%.[15] Therefore I assume that the total processing losses (both reprocessing and metal fabrication) were only about 2 percent.

The amount of plutonium that might have been consumed in North Korea's six nuclear tests depends in part on the yield of these tests. Estimates of the test yields have varied. For this paper I rely on a sophisticated 2019 analysis of the seismic effects of the tests.[16] For North Korea's 2006 and 2009 tests, plutonium must have been used since North Korea probably did not have access to HEU at those times. North Korea has stated that it used 2 kilograms of plutonium for its first nuclear test. Some have been skeptical of this statement but such a small quantity of plutonium is consistent with this test's low yield (1.4 kilotons). Similarly, I estimate that the second nuclear test with a yield of 5 kilotons used only 3 kilograms of plutonium.

North Korea's third nuclear test occurred after North Korea had probably acquired HEU but was at a time when there was a lengthy shutdown of the Yongbyon reactor. Therefore, I assume that North Korea used HEU and given the test's yield (13.2 kilotons) about 20 kilograms would have been used. North Korea's fourth nuclear test occurred before North Korea would have acquired the additional plutonium from cycle 4. Therefore, I assume that this test also used HEU and given its yield (11.2 kilotons) about 20 kilograms would have been used. North Korea's fifth nuclear test occurred after North Korea would have recovered the plutonium from the Yongbyon reactor's cycle 4. I assume that this test used plutonium and given its yield (18.8 kilotons) about 5 kilograms would have been used.

North Korea's sixth nuclear test had a much higher yield (250 kilotons). I have previously written about the possible designs of this test device and how much nuclear material might have been in the device.[17] This device could have been a simple fission weapon employing a large amount of HEU to achieve its high yield similar to the U.S. King device tested in 1952. I estimated that such a device could require between 40 to 60 kilograms of HEU. The test device could also have been some sort of two-stage thermonuclear weapon (hydrogen bomb). I have estimated that such a device could have solely used HEU and that somewhere between 30 to 50 kilograms would have been required. It is also possible that North Korea used a plutonium primary in its two-stage thermonuclear test device. This primary could have used about 5 kilograms of plutonium.

To be conservative, I assume that 5 kilograms of plutonium was used in North Korea's sixth nuclear test. Adding in the amounts used in the first, second and fifth nuclear tests the total plutonium consumed in the nuclear tests would be 15 kilograms. Also taking into account the

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[15] David Albright with Andrea Stricker, *Revisiting South Africa's Nuclear Weapons Program*, Institute for Science and International Security, June 2016, p. 66. https://isis-online.org/uploads/isis-reports/documents/RevisitingSouthAfricasNuclearWeaponsProgram.pdf

[16] Dimitri P. Voytan, Thorne Lay, Esteban J. Chaves, and John T. Ohman, "Yield Estimates for the Six North Korean Nuclear Tests From Teleseismic P Wave Modeling and Intercorrelation of P and Pn Recordings," *Journal of Geophysical Research: Solid Earth*, Vol. 124, May 23, 2019, p. 4934, Table 7, *pP*Time 1.25, 4% grade. https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019JB017418

[17] Gregory S. Jones, "Constraints on Possible High Yield North Korean Nuclear Weapons: Weight and Nuclear Materials Requirements," August 24, 2021. https://nebula.wsimg.com/61d3180db8bdb240efe514099be86a6f?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1

2% processing losses, North Korea's current plutonium stocks would be about 85 kilograms. The amount of HEU consumed in the nuclear tests is around 100 kilograms.

My estimate of North Korea's current plutonium stocks is significantly greater than several other estimates. Albright gives an estimate of 56 to 70 kilograms with a median of 63 kilograms.[18] Albright provides no details as to how he derived his estimate. Siegfried Hecker, senior fellow and professor emeritus at Stanford University and director emeritus of the Los Alamos National Laboratory, gives a lower estimate of 25 to 48 kilograms.[19] This estimate may not have included the plutonium North Korea recovered from cycle 5 of the Yongbyon reactor but this probably would only raise his estimate by 10 to 20 kilograms. His estimate would still be below Albright's and well below mine. Hecker does not provide details of how he derived his estimate. Without more details as to how Albright and Hecker produced their estimates, I cannot explain the differences between their estimates and mine.

Possible future growth in plutonium stocks and the Experimental Light Water Reactor

Looking to the future, North Korea's plutonium stocks will continue to grow. Cycle 6 at the 25 MWt Yongbyon reactor began in July 2021. Based on cycle 5, the fuel from cycle 6 will probably be discharged in the summer of 2024. The fuel will need to cool for about 4 months, and then another four to six months will be required to reprocess all the fuel. As a result, in the first half of 2025, North Korea will probably acquire another 20 kilograms of plutonium.

A more significant development is that in October 2023 North Korea started operating a second nuclear reactor at Yongbyon. In 2010 North Korea stated that it was planning to build a small light-water power reactor. Hecker visited the site where the construction was just beginning and was told that the reactor was intended to have a power of 100 MW (thermal).[20] This power level would imply an electrical output of perhaps 30 MW. Such a reactor could be used to produce plutonium, though its output would be less than that of a dedicated plutonium production reactor. Also, a new head-end would need to be added to North Korea's reprocessing plant to handle the oxide fuel that would be used in such a reactor. Because of the North Korean statements, the reactor is referred to as the "Experimental Light-Water Reactor" (ELWR).

Jeffrey Lewis of the Middlebury Institute at Monterey, has pointed out that North Korea's state media has not referred to the experimental light-water reactor since 2012.[21] Exactly what kind of reactor has been built at the ELWR site is unknown as the reactor is hidden inside of the reactor containment structure. According to Albright, some European intelligence officials believe that

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[18] David Albright, "North Korean Nuclear Weapons Arsenal: New Estimates of its Size and Configuration," Institute For Science and International Security, April 10, 2023. https://isis-online.org/uploads/isis-reports/documents/North_Korean_Nuclear_Weapons_Arsenal_New_Estimates_of_its_Size_and_Configuration_April_10_2023.pdf

[19] "Estimating North Korea's Nuclear Stockpiles: An Interview With Siegfried Hecker," 38 North, April 30, 2021. https://www.38north.org/2021/04/estimating-north-koreas-nuclear-stockpiles-an-interview-with-siegfried-hecker/

[20] Siegfried S. Hecker with Elliot A. Serbin, *Hinge Points: An Inside Look at North Korea's Nuclear Program*, Stanford University Press, 2023, p. 238.

[21] Jeffrey Lewis, "North Korea's ELWR Now Appears Operating," Arms Control Wonk, December 21, 2023. https://www.armscontrolwonk.com/archive/1219037/north-koreas-elwr-now-appears-operating/

the reactor could be a water-cooled graphite moderated reactor.[22] The U.S. built nine such reactors at Hanford in the 1940s, 50s and 60s to function as plutonium production reactors. Using the reactor to produce plutonium would be better in keeping with Kin Jong Un's desire to rapidly expand his nuclear weapons arsenal than would a reactor designed to produce small amounts of electricity. In order to consider a case where the focus of the ELWR is the production of plutonium, I assume that the reactor at the ELWR reactor site is a natural uranium fueled, graphite moderated, light-water cooled reactor. However, it should be recognized that the actual reactor design is rather uncertain and I will also consider the case where the ELWR is a LWR.

For the case where the ELWR is a graphite moderated, natural uranium fueled reactor, I assume that the fuel inventory of this reactor is 50 metric tons, the same as that of the 25 MWt reactor that is already at Yongbyon. This latter reactor is gas-cooled and only has a power density of 0.5 MW/MT of fuel. The advantage of having a water-cooled reactor is that it can have a much higher power density resulting in a higher power level and plutonium production. Based on U.S. experience at Hanford, it would be easy for the reactor to have a power density of 1.5 MW/MT, which would give a reactor power level of 75 MW. Assuming a target fuel burnup of 450 MWD/MT and that the reactor operates 300 days per year, the fuel would reach its target burnup in exactly one year. The fuel would contain about 20 kilograms of plutonium.

North Korea's reprocessing plant at Yongbyon has reprocessed the 50 metric tons discharged from the 25 MWt reactor at Yongbyon in about 4 or 5 months which implies a capacity of at least 100 metric tons per year. North Korea's reprocessing plant would seem to have sufficient capacity to handle an additional 50 metric tons of fuel per year from the new reactor.

A more serious problem is providing enough uranium to fuel the reactor (North Korea's natural uranium production is discussed below). The current 25 MWt reactor at Yongbyon has been fueled five times between the beginning of 2003 and mid-2021. This required 250 metric tons of uranium over an 18.5 year period, which is an average of about 14 metric tons per year. My hypothesized new reactor would require 50 metric tons of uranium per year for a total of about 64 metric tons of uranium per year being consumed in the reactors. This would be in addition to the uranium that North Korea is using to produce HEU. It is not clear that North Korea's mining operations can produce this much uranium, though perhaps North Korea has started importing uranium from Russia.

Considering the case where the ELWR is in fact an LWR, then the numbers would be rather different. The reactor as was described to Hecker in 2010[23] used fuel that was enriched to 3.5% and four metric tons of uranium were contained in the core. With a 100 MW thermal output and the reactor operating 300 days per year, then the fuel would reach a nominal full burnup in four years (30,000 MWD/MT). At equilibrium, one-quarter of the core would need to be replaced each year which is one metric ton. To produce the replacement fuel would require 7.3 metric

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[22] David Albright, Sarah Burkhard, Victoria Cheng and Spencer Faragasso, "North Korea's ELWR: Finally Operational After a Long Delay," Institute for Science and International Security, January 23, 2024, p. 5. https://isis-online.org/uploads/isis-reports/documents/North_Koreas_ELWR_January_2024_Final.pdf

[23] Siegfried S. Hecker with Elliot A. Serbin, *Hinge Points: An Inside Look at North Korea's Nuclear Program*, Stanford University Press, 2023, p. 238-239.

tons of natural uranium instead of the 50 metric tons of fuel used in my hypothesized natural uranium fueled ELWR.[24] The enriched fuel would also require 4,600 SWU/yr of enrichment capacity, which would reduce North Korea's HEU production by about 23 kilograms per year.

The plutonium production would be about 10 kilograms per year. This plutonium would be reactor-grade, though as I have written elsewhere, by reducing the plutonium core size in the weapons and accepting a reduced yield, this plutonium could be used without any serious concerns with regard to predetonation.[25]

At any rate all we know for sure is that some type of new reactor has started at Yongbyon. Though satellite observations can reveal the reactor's hot water discharge, we cannot determine the reactor's power level or even what type of reactor it is. If my hypothesis of a graphite moderated, natural uranium fueled, water-cooled reactor is close to being correct, then the reactor will need to shutdown to refuel in the fall of 2024 and the fuel would be reprocessed sometime in the first half of 2025. Further observations of this new reactor may help narrow down the uncertainty.

Boosted Nuclear Weapons and Tritium

Boosting is an important advancement in nuclear weapons design. Boosted weapons use hollow cores of nuclear material. Just before detonation, a tritium/deuterium gas mixture is inserted into this hollow space. The detonation of the weapon causes a fusion reaction. The energy release from the fusion reaction is small and does not significantly increase the yield of the fission weapon. However, the fusion reaction releases a large number of high energy neutrons which greatly increases the efficiency of the fission reaction.

Many experts mistakenly believe that this increased efficiency is used to increase the yield of the weapon to produce high yield weapons but that is usually not its purpose. As the British have said, "But there was another way to look at boosting. Instead of using it to *increase* the yield of a warhead of given size and fissile content, it could be used to *reduce* the size and fissile content of a warhead while maintaining or even improving the yield."[26][Emphasis in original] Therefore boosting is a means to increase the number of weapons that can be produced from a given quantity of nuclear material and make the weapons more deliverable.

Not only is boosting a method for making better fission nuclear weapons, but boosting is the key to producing reliable two-stage thermonuclear weapons (hydrogen bombs). As the name implies, two-stage nuclear weapons consist of two components, a relatively low yield fission primary and a thermonuclear burning secondary which produces most of the yield. The primary need not be boosted and indeed, early U.S., British and Soviet two-stage weapons were not. However, unboosted primaries are vulnerable to predetonation which could be caused by neutrons from either spontaneous fission or from nearby nuclear detonations, such as from either

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[24] 0.27% tails.

[25] Gregory S. Jones, "Technical Appendix to 'Reactor-Grade Plutonium and Nuclear Weapons: Ending the Debate' published in the Nonproliferation Review, 2019," pp. 13-16. https://nebula.wsimg.com/4eb6ba13bee5765c8e2aec7d658c7cde?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1

[26] Lorna Arnold, *Britain and the H-Bomb*, UK Ministry of Defense, Palgrave, 2001, p. 177.

defensive warheads or nearby “friendly” weapons. If the primary predetonates, its reduced yield may not be enough to cause sufficient reaction in the secondary and the weapon’s yield could be greatly reduced.

As the British have stated, the advantage of using boosted nuclear fission weapons is that they are “immune” to predetonation, ensuring that the weapon will produce its full yield.[27] The use of boosted primaries in two-stage thermonuclear weapons solves the predetontion problem. At present all U.S., British and French nuclear weapons are two-stage weapons that use boosted primaries.

The deuterium required for boosted weapons can be extracted from ordinary water, but tritium only exists in trace amounts in nature and must be produced by either irradiating lithium in nuclear reactors or by recovering the tritium produced in the moderator of heavy water nuclear reactors. Since tritium has a half-life of 12.3 years, each year 5.5% of the tritium decays away. Therefore, regular production is required to maintain a fixed amount of tritium. Though prior estimates by other analysts of North Korea’s nuclear arsenal recognized that North Korea may be producing some tritium, none of these other estimates have attempted to quantify possible North Korean tritium stocks.

North Korea does not have any heavy water nuclear reactors and like all other nuclear weapons states, it would need to irradiate lithium in some nuclear reactor to produce tritium. North Korea has only had two nuclear reactors, the 25 MWt plutonium production reactor at Yongbyon and a Soviet supplied IRT research reactor with a power output of 8 MWt.

Natural uranium-fueled reactors such as the 25 MWt plutonium production reactor have only a limited amount of excess reactivity. Given the strong neutron absorbing characteristics of lithium, all reactors that have produced tritium have used enriched uranium. Due to their different masses, a gram of tritium is equivalent to 79.3 grams of plutonium. If a neutron that would have produced plutonium instead produces tritium, the lost mass of plutonium is 79.3 times as much as the tritium produced. However, work at Hanford showed that some tritium could be produced by using neutrons that were otherwise wasted by escaping from the reactor or were absorbed in reactor structural materials. Therefore, the actual reduction in plutonium production was somewhat less.

Based on the Hanford analysis, if the 25 MWt reactor used fuel enriched to 1%, then the reactor could produce about 23 grams of tritium per year.[28] This would be at the expense of lowering the reactor’s plutonium production from 6.8 kilograms per year to 5.8 kilograms per year. If the reactor used 1.2% enriched fuel, then the reactor could produce about 32 grams of tritium per year at the expense of reducing its plutonium production to about 5.1 kilograms of plutonium per year.

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[27] Ibid.

[28] At 300 days of operation per year. “Hanford Reactor and Separations Facility Advantages,” HW-78100, Hanford Atomic Products Operation, Richland, Washington, June 27, 1963, p. 20. https://www.osti.gov/servlets/purl/10184818

Since North Korea did not have substantial enrichment capacity before 2010, North Korea could only have started using enriched fuel in the 25 MWt reactor for cycles 4, 5 and 6. Taking into account the tritium decay since the discharge of cycles 4 and 5 and that any possible tritium from cycle 6 has not yet been recovered, at the end of 2023 North Korea could have a tritium stockpile of about 82 grams if it used 1% enriched fuel and about 117 grams if it used 1.2% enriched fuel. North Korea's total plutonium stockpile would be reduced by 5 kilograms if it used 1% enriched fuel and 8 kilograms if it used 1.2% enriched fuel. Including the fuel required for cycle 6, these three reactor fuel loads would require around 45,000 SWU and 250 metric tons of natural uranium if it used 1% enriched fuel and around 84,000 SWU and 320 metric tons of natural uranium if it used 1.2% enriched fuel.[29] In contrast, without producing any tritium, three reactor fuel loads of natural uranium would require only 150 metric tons and no enrichment.

The IRT reactor originally started operation in the 1960s with a power level of 2 MWt. Its power was increased several times, so that it currently has a power of 8 MWt. The reactor relied on fuel supplied by the Soviet Union, but this supply stopped in 1991 and to conserve fuel, the reactor only operated intermittently. In 2016, Albright reported that the reactor had restarted operation using North Korean supplied enriched uranium fuel though there had been an accident that caused several fuel elements to melt.[30] In 2022, the IAEA confirmed that the reactor had probably restarted but that its operation was "infrequent, [and] short-term."[31] If the reactor could operate on a sustained basis (250 days per year), it could perhaps produce about 1 kilogram of plutonium per year or about 13 grams per year of tritium.[32] Given the intermittent operation of this reactor, it has produced far less than these amounts and I assume that, though it may have produced small research quantities of plutonium and/or tritium, the reactor has not significantly added to North Korea's stockpile of either material.

Data from the U.S. use of tritium in its nuclear weapons provides a means to convert the quantity of total tritium into the number of nuclear weapons. I have elsewhere calculated that the U.S. was planning to use about 4.5 to 5.0 grams of tritium per weapon due in part to the lack of nuclear testing since 1992.[33] The U.S. keeps a 5 year tritium reserve (about one quarter of the total tritium stockpile) to cover possible interruptions in production. Given that North Korea has only one reactor that can provide tritium, it might want to keep a larger tritium reserve. If half of the tritium stockpile is kept in reserve, then the reserve would last 12.3 years.

North Korea's tritium stockpile is not nearly large enough to boost all of its nuclear weapons. Even if North Korea uses only 4.5 grams of tritium per weapon and a 5 year reserve, then about

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[29] 0.27% tails.

[30] David Albright and Serena Kelleher Vergantini, "North Korea's IRT Reactor: Has it Restarted? Is it Safe?," Institute for Science and International Security, March 9, 2016. https://isis-online.org/uploads/isis-reports/documents/IRT_Reactor_March_9_2016_FINAL.pdf

[31] "Application of Safeguards in the Democratic People's Republic of Korea," GOV2022/40-GC(66)/16, International Atomic Energy Agency, September 7, 2022, p. 6. https://www.iaea.org/sites/default/files/gc/gc66-16.pdf

[32] F. T. Binford, "Diversion Assumptions For High-Powered Research Reactors," ORNL-6022, Oak Ridge National Laboratory, January 1984, p. 5. https://www.osti.gov/servlets/purl/5955646

[33] Gregory S. Jones, "U.S. Increased Tritium Production Driven by Plan to Increase the Quantity of Tritium per Nuclear Weapon," June 2, 2016. https://nebula.wsimg.com/08a60104185a91e6db9008fb929a0873?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1

6 grams of tritium would be required per weapon. Assuming the high end stockpile of 117 grams, only about 19 weapons could be boosted. Assuming 5 grams of tritium per weapon and a 12.3 year reserve, only about 12 weapons could be boosted. Note that the enriched uranium required to fuel the 25 MWt Yongbyon reactor to produce the 117 gram stockpile would require reducing North Korea's production of HEU by about 420 kilograms. If the tritium stockpile is 82 grams, then the number of possible boosted weapons becomes about 14 weapons and 8 weapons respectively. The enriched uranium required to produce the 82 gram tritium stockpile would require reducing North Korea's production of HEU by about 220 kilograms.

As stated above, maintaining a tritium stockpile requires continuing production. However, the long shutdown of the 25 MWt Yongbyon reactor between October 2018 and July 2021 might reflect that producing tritium is not currently a major priority for North Korea. Also, given that even using full core loads of enriched uranium fuel would only allow North Korea to boost a small part of its nuclear weapons stockpile, I believe that North Korea has not yet used the 25 MWt reactor at Yongbyon as a major source of tritium. More likely it has only used partial loads of enriched uranium to produce small amounts of tritium. As a result, as of the end of 2023, no more than a small number of North Korean nuclear weapons were probably boosted. Note this situation could change with the start of the ELWR.

Highly Enriched Uranium

In November 2010 a delegation from Stanford University that was touring North Korea's Yongbyon nuclear site was stunned when they were shown a newly completed centrifuge uranium enrichment plant. According to Hecker, who was part of the delegation, the North Koreans stated that the plant had an enrichment output of 8,000 SWU per year and was producing uranium with an enrichment of 3.5% with a tails of 0.27%. The facility appeared to contain about 2,000 centrifuges, which results in an output of 4 SWU per centrifuge-year. This centrifuge output is consistent with early technology that Pakistan stole from the European centrifuge enrichment consortium URENCO. Pakistan has stated that it passed this technology along to North Korea.

By the end of 2013 North Korea had doubled the size of this facility. No Westerner has been inside the expanded facility, but it is assumed that the enrichment capacity was doubled to 16,000 SWU per year. Though the North Koreans stated that it was producing uranium enriched to 3.5%, it would be easy to have this plant produce 90% highly enriched uranium (HEU). If operated optimally, this enrichment capacity would produce 79 kilograms of HEU per year.[34]

Most analysts also believe that North Korea has additional enrichment sites hidden at locations away from Yongbyon. At a minimum, Hecker believes that there must have been a pilot plant where North Korea developed its centrifuge production capabilities. Others have suggested that North Korea could have at least one large-scale hidden facility. Indeed, the high estimates of North Korea's centrifuge enrichment capacity are rather open-ended, since it could have many more than the 4,000 centrifuges believed to be at Yongbyon. Therefore, two different approaches have been used to try to constrain North Korea's centrifuge enrichment capacity.

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[34] 0.27% tails.

A Stanford group, including Hecker, attempted to estimate how many centrifuge components North Korea has been able to procure. Their median estimate gives an enrichment capacity of 35,400 SWU per year.[35] But this is not a very firm high-end constraint. They believe that there is a 25% chance that North Korea has an enrichment capacity of 60,800 SWU per year and that there is about a 10% chance that it exceeds 85,000 SWU per year.

Another approach is to try to determine North Korea's natural uranium mining production. Melissa Hanham et. al. of the Middlebury Institute of International Studies at Monterey has attempted to address this problem by examining North Korea's mining facilities using satellite photos.[36] They conclude that North Korea's natural uranium production could be quite large, between 273 to 886 metric tons per year. However, this estimate assumes a high uranium ore concentration of between 2,600 and 8,000 parts per million (ppm).

Another Stanford group, Sulgiye Park et. al., has determined that North Korea is mining a shale type deposit.[37] This type of deposit has a rather low uranium concentration. Given North Korea's ore production and assuming a relatively high uranium ore concentration (for a shale type deposit) of 300 ppm, North Korea could be producing about 90 metric tons of uranium per year. Since the assumed uranium ore of 300 ppm is towards the high end for shale type deposits, I, instead, assume a more realistic ore concentration of 200 ppm, which gives an annual uranium production of 60 metric tons. I will use this value of 60 metric tons of uranium production per year to set an upper limit on North Korea's HEU production and its nuclear weapon related activities in general.

If the 25 MWt reactor at Yongbyon is only producing plutonium, its natural uranium fuel requirements are not that large. The reactor was refueled with total core replacements five times between 2003 and mid-2021, giving an average natural uranium consumption of 14 metric tons per year. During this period the reactor was shutdown for long periods but even if one assumes that in the future the reactor operates without long shutdowns and refuels once every three years as it did with its most recent cycle 5, the reactor would only consume about 17 metric tons of natural uranium per year. This amount is well within North Korea's production capability.

If the 25 MWt reactor were to be used for tritium production, its natural uranium requirements would increase significantly. If it were to be operated continuously, and used fuel with a 1% enrichment, then instead of 17 metric tons of natural uranium per year, the reactor would require about 28 metric tons of natural uranium per year. If it were to use fuel with a 1.2% enrichment, then it would require about 36 metric tons of natural uranium per year. North Korea could only provide these larger amounts of natural uranium by restricting its uranium enrichment activities.

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[35] John E. Bistline, et. al., "A Bayesian Model to Assess the Size of North Korea's Uranium Enrichment Program," *Science and Global Security*, Vol. 23, 2015, p. 83. https://scienceandglobalsecurity.org/archive/sgs23bistline.pdf

[36] Melissa Hanham, et. al., "Monitoring Uranium Mining and Milling in China and North Korea through Remote Sensing Imagery," CNS Occasional Paper #40, Middlebury Institute of International Studies at Monterey, October 2018, p. 11. https://www.nonproliferation.org/wp-content/uploads/2018/10/op40-monitoring-uranium-mining-and-milling-in-china-and-north-korea-through-remote-sensing-imagery.pdf

[37] Sulgiye Park, et. al., "Assessing Uranium Ore Processing Activities Using Satellite Imagery at Pyongsan in the Democratic People's Republic of Korea," *Science & Global Security*, Vol. 29, No.3, 2021, p. 113. https://scienceandglobalsecurity.org/archive/sgs29park.pdf

Estimates of North Korean HEU Production Rate and Implied Natural Uranium Requirements

The implied amount of natural uranium consumed by North Korea's enrichment activities depends upon the specific assumptions made regarding its enrichment plants. I will examine five different estimates.

In 2021, Olli Heinonen, who has been deputy director general of the IAEA and head of its Department of Safeguards, assumed that North Korea was only using the enrichment plant at Yongbyon.[38] He assumes an enrichment capacity of 16,000 SWU and tails of 0.4%. If used to produce HEU, the rate would be 94 kilograms per year, consuming 27 metric tons of natural uranium per year.

Heinonen has also suggested that North Korea could be using the enrichment plant at Yongbyon to produce only 3.5% enriched uranium. He then suggested that North Korea could be shipping this 3.5% enriched uranium to a clandestine "topping" enrichment site, which would then enrich the 3.5% enriched uranium to 90% enriched uranium. Heinonen has not provided any calculations of the amount of 90% enriched uranium per year that could be produced by this method. However, I have calculated that if the Yongbyon plant has an enrichment capacity of 16,000 SWU per year and used 0.27% tails, a topping plant could produce 108 kilograms of HEU, while consuming 22 metric tons of natural uranium per year. The topping enrichment plant would need to contain about 1,460 centrifuges.

In 2016, Hecker assumed that North Korea had a clandestine pilot plant with 660 centrifuges, a clandestine full-scale enrichment plant with 4,000 centrifuges and that the known plant at Yongbyon had 4,000 centrifuges.[39] Assuming 4 SWU per year output per centrifuge, this gives a total enrichment output of 34,640 SWU. With 0.275% tails, this produces about 173 kilograms of HEU per year requiring 35.7 metric tons of natural uranium per year.[40]

In 2017, Albright presented two scenarios for North Korea's HEU production. In his first case, there was only enrichment at the Yongbyon site.[41] He assumed 3,000-4000 centrifuges, which due to inefficiencies, only produced 3.25 SWU per centrifuge per year. He assumes tails between 0.3% and 0.4%. His analysis gives a median HEU production rate of 58 kilograms per year. This result can be obtained by assuming 3,500 centrifuges with tails of about 0.3%. These assumptions require about 13 metric tons of natural uranium per year.

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[38] Olli Heinonen, "Development of the Yongbyon Uranium Enrichment Plant Between 2009 and 2021," 38 North, July 16, 2021. https://www.38north.org/2021/07/development-of-the-yongbyon-uranium-enrichment-plant-between-2009-and-2021/

[39] Chaim Braun, Siegfried Hecker, Chris Lawrence, and Panos Papadiamantis, "North Korean Nuclear Facilities After the Agreed Framework," Center for International Security and Cooperation, Stanford University, May 27, 2016, p. 50. https://fsi.stanford.edu/publication/north-korean-nuclear-facilities-after-agreed-framework

[40] Braun et. al. leave out the pilot plant centrifuges and state that the HEU production is only 150 kilograms per year. (ibid., p. 53) However, in 2021, Hecker apparently added in these extra centrifuges which results in HEU production which is "on the order of 175 kg per year." See "Estimating North Korea's Nuclear Stockpiles: An Interview With Siegfried Hecker," 38 North, April 30, 2021. https://www.38north.org/2021/04/estimating-north-koreas-nuclear-stockpiles-an-interview-with-siegfried-hecker/

[41] David Albright, "North Korea's Nuclear Capabilities: A Fresh Look," Institute for Science and International Security, April 22, 2017, pp. 18-22. https://isis-online.org/uploads/isis-reports/documents/North_Korea_Nuclear_Capability_Estimates_Summary_28Apr2017_Final.pdf

In his second case, he assumes an additional clandestine enrichment plant with characteristics the same as those of the enrichment plant at Yongbyon. This assumption doubles the HEU production rate to 116 kilograms per year and the natural uranium required to 26 metric tons per year. By making various assumptions, Albright assumes that at the end of 2016, the median of North Korea's total HEU stockpile for the first case was 175 kilogram and for the second case 644 kilograms.

However, in 2023, Albright gives the median of North Korea's total HEU stockpile for the end of 2022 as 1,770 kilograms.[42] Compared to his estimates for North Korea's HEU stockpile size at the end of 2016, this would require an average HEU production rate of between 266 and 188 kilograms per year, respectively, to reach his estimated North Korean HEU stockpile size in 2022. These higher average production rates would require between 58 and 41 metric tons of natural uranium per year, respectively. Albright does not explain how his assumptions about North Korea's enrichment program have changed to produce these higher HEU production rates.

In 2021, a joint RAND/Asan report assumed that North Korea could have up to 22,000 centrifuges.[43] With an output of 4 SWU per year per centrifuge and operated with an efficiency of 80%, these centrifuges would produce 70,400 SWU per year. Using 0.275% tails, this results in the production of 352 kilograms of HEU per year requiring 72.5 metric tons of natural uranium per year. The RAND/Asan report also assumes an alternate case with a lower HEU production rate which is two-thirds that of the high production rate, giving an annual HEU production rate of 235 kilograms, requiring 48.3 metric tons of natural uranium.

Estimates of North Korea's HEU Stockpile

These various HEU production rates lead to various estimates of North Korea's current HEU stockpile, which are summarized in Table 2. Heinonen estimates that North Korea could have produced 705 kilograms of HEU by the end of 2020.[44] He estimates that some enriched uranium production went to producing low enriched uranium fuel for the ELWR, which would lower the stockpile to just 540 kilograms of HEU. However, as was discussed above, it is not clear that the "ELWR" is actually an LWR or that it uses enriched uranium fuel. Therefore, I consider 705 kilograms to be a better estimate. Assuming that North Korea has continued producing HEU at the same rate, by the end of 2023, North Korea would have about 1,000 kilograms of HEU.

For the clandestine topping enrichment case that Heinonen suggested but did not calculate, using his same assumptions as to when various enrichment capacities became available, North Korea's HEU stockpile at the end of 2023 would be about 1,100 kilograms.

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[42] David Albright, "North Korean Nuclear Weapons Arsenal: New Estimates of its Size and Configuration," Institute for Science and International Security, April 10, 2023, p. 8. https://isis-online.org/uploads/isis-reports/documents/North_Korean_Nuclear_Weapons_Arsenal_New_Estimates_of_its_Size_and_Configuration_April_10_2023.pdf

[43] Bruce W. Bennett et. al. "Countering the Risks of North Korean Nuclear Weapons," RAND/Asan, April 2021, pp. 36-37. file:///C:/Users/gjones/Downloads/RAND_PEA1015-1.pdf

[44] Olli Heinonen, "Development of the Yongbyon Uranium Enrichment Plant Between 2009 and 2021," 38 North, July 16, 2021. https://www.38north.org/2021/07/development-of-the-yongbyon-uranium-enrichment-plant-between-2009-and-2021/

Table 2

Various Estimates of North Korea's HEU Production Facilities, Their Implied Natural Uranium Requirements, Their Production Capacity of HEU and North Korea's Total HEU Stockpile as of the End of 2023

Estimator	N. Korean Enrichment Facilities (# Centrifuges)	HEU Production Rate (Kilograms per Year)	Implied Natural Uranium Requirements (Metric Tons per Year)	Total North Korean HEU Stockpile End of 2023 (Kilograms)
Heinonen	Yongbyon Only (4,000)	94	27	~1,000*
Heinonen Alternate (My Calculations)	Yongbyon Plus Clandestine Topping Plant (~5,500)	108	22	~1,100
Hecker	Yongbyon Plus Clandestine Pilot Plant Plus Clandestine Full-Sized Plant (~9,000)	175	36	~1,100 to ~1,500**
Albright	Yongbyon Plus Clandestine Full-Sized Plant Plus Additional Plants (~11,000 to ~16,000)	188 to 266	41 to 58	~2,000***
RAND/Asan	Yongbyon Plus Two Large Clandestine Plants (~15,000 to 22,000)	235 to 352	48 to 73	~1,900 to ~3,100
This Author	Yongbyon Plus Clandestine Topping Plant Plus Possible Additional Large Clandestine Plant (5,500 to 10,000)	110 to 200	22 to 41	1,000 to 1,900

*Author's extrapolation from Heinonen's end 2020 estimate
** Author's extrapolation from Hecker's end 2020 estimate
*** Author's extrapolation from Albright's end 2022 estimate

Hecker has estimated that North Korea's HEU stockpile was 600 to 950 kilograms at the end of 2020.[45] Assuming that North Korea's production rate continues at the same rate as Hecker has estimated, then at the end of 2023 North Korea's HEU stockpile would be about 1,100 to 1,500 kilograms.

As was stated above, Albright gives a median estimate of North Korea's HEU stockpile at the end of 2022 as 1,770 kilograms.[46] He appears to estimate that North Korea is continuing to produce about 230 kilograms of HEU per year, so that by the end of 2023, North Korea would have a stockpile of HEU of about 2,000 kilograms.

RAND/Asan projects that by the end of 2023, North Korea will have between 103 and 170 nuclear weapons.[47] Between 6 and 13 weapons likely use plutonium, leaving between 97 and 157 weapons that use HEU. RAND/Asan assumes 20 kilograms of HEU per weapon giving North Korea a HEU stockpile of between 1,940 to 3,140 kilograms.

My Synthesis of These Estimates

These estimates provide a wide range between about 1,000 kilograms to 3,100 kilograms for North Korea's HEU stockpile with associated HEU annual production rates of about 100 kilograms to 350 kilograms respectively. Natural uranium production considerations would seem to rule out the high-end stockpiles and annual HEU production rates, since the natural uranium requirements would be over 70 metric tons per year.

Similarly, natural uranium requirements would seem to rule out North Korea using the 25 MWt reactor at Yongbyon to produce substantial quantities of tritium. If the reactor were to use fuel enriched to 1.2% instead of natural uranium, the annual natural uranium needed would more than double from 17 metric tons to 36 metric tons. Yet the tritium produced would allow North Korea to boost no more than about 19 weapons. Lowering the fuel enrichment to 1%, reduces the annual natural uranium requirements to 28 metric tons, but the tritium produced only allows for no more than about 14 weapons to be boosted.

For a minimum case, I use the alternate Heinonen case that I calculated resulting in an annual HEU production rate of about 110 kilograms. This would require only 22 metric tons of natural uranium per year.[48] The resulting HEU stockpile is 1,100 kilograms. Subtracting the about 100 kilograms consumed in nuclear weapon tests gives a HEU stockpile of 1,000 kilograms.

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[45] "Estimating North Korea's Nuclear Stockpiles: An Interview With Siegfried Hecker," 38 North, April 30, 2021. https://www.38north.org/2021/04/estimating-north-koreas-nuclear-stockpiles-an-interview-with-siegfried-hecker/

[46] David Albright, "North Korean Nuclear Weapons Arsenal: New Estimates of its Size and Configuration," Institute for Science and International Security, April 10, 2023, p. 8. https://isis-online.org/uploads/isis-reports/documents/North_Korean_Nuclear_Weapons_Arsenal_New_Estimates_of_its_Size_and_Configuration_April_10_2023.pdf

[47] Bruce W. Bennett et. al. "Countering the Risks of North Korean Nuclear Weapons," RAND/Asan, April 2021, p 37. file:///C:/Users/gjones/Downloads/RAND_PEA1015-1.pdf

[48] 0.27% tails

For a high-end case I use an annual HEU production rate of 200 kilograms per year. This would require 41 metric tons of natural uranium per year which is about as much as North Korea's natural uranium production can support. Combined with the 14 metric tons per year that has been required by the Yongbyon reactor, this would add up to 55 metric tons per year which would be within North Korea's natural uranium production capabilities. Assuming North Korea produced 200 kilograms of HEU per year for ten years, it would have a stockpile of 2,000 kilograms. Subtracting the about 100 kilograms consumed in nuclear weapon tests gives a HEU stockpile of 1,900 kilograms.

Total Nuclear Material Stockpile and Total Number of North Korean Nuclear Weapons

My Estimates

As a result of this analysis, my estimate of North Korea's nuclear material stockpiles at the end of 2023 is 85 kilograms of plutonium, 1,000 to 1,900 kilograms of HEU and little or no tritium. If converted into the number of weapons, assuming 5 kilograms of plutonium per weapon and 20 kilograms of HEU per weapon results in an estimate of 67 to 112 weapons. Despite this large uncertainty range, it is clear that North Korea possesses a sizable nuclear arsenal.

The annual HEU production rate of 110 to 200 kilograms converts into about 5 to 10 weapons per year. With the Yongbyon reactor producing about one weapon's worth of plutonium per year, based on its current capabilities, North Korea's weapons stockpile would grow at the rate of 6 to 11 weapons per year.

Of course, it is known that one can make a nuclear weapon with less than 5 kilograms of plutonium or 20 kilograms of HEU. Albright gives a range for the amount of plutonium in a nuclear weapon of between 2 to 5.8 kilograms with a mean of 3.5 kilograms.[49] However, as I have written elsewhere, reducing the amount of nuclear material in a nuclear weapon reduces the yield as well.[50] Albright does not address this issue but I estimate that using just 3.5 kilograms of plutonium would reduce the yield from about 20 kilotons to around 8 kilotons. Using just 2 kilograms of plutonium would reduce the yield to around 1 kiloton. Similarly, Albright uses a range of between 15 and 25 kilograms for the amount of HEU per weapon, which again would result in a range of yields.

Further as was discussed above, high yield North Korean weapons such as the 250 kiloton device tested in 2017 can use between 30 and 60 kilograms of HEU per weapon.[51] Assuming 50

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[49] David Albright, "North Korean Nuclear Weapons Arsenal: New Estimates of its Size and Configuration," Institute for Science and International Security, April 10, 2023, p. 10. https://isis-online.org/uploads/isis-reports/documents/North_Korean_Nuclear_Weapons_Arsenal_New_Estimates_of_its_Size_and_Configuration_April_10_2023.pdf

[50] Gregory S. Jones, "Technical Appendix to 'Reactor-Grade Plutonium and Nuclear Weapons: Ending the Debate' published in the Nonproliferation Review, 2019," pp. 13-16. https://nebula.wsimg.com/4eb6ba13bee5765c8e2aec7d658c7cde?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1

[51] Gregory S. Jones, "Constraints on Possible High Yield North Korean Nuclear Weapons: Weight and Nuclear Materials Requirements," August 24, 2021. https://nebula.wsimg.com/61d3180db8bdb240efe514099be86a6f?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1

kilograms per weapon would significantly reduce the number of North Korean nuclear weapons. This point illustrates that without taking into account weapons yield, the number of North Korean nuclear weapons is only a partial measure of North Korea's nuclear arsenal. Indeed, North Korea probably uses a range of nuclear material amounts in its weapons. Some low yield tactical weapons probably use less nuclear material and some high yield weapons use significantly more. Without knowing more about the yields of North Korea's nuclear weapons, there is no way to refine my estimate of 67 to 112 weapons.

Importantly, North Korea does not have significant quantities of tritium. Without tritium, it is not possible to build small lightweight thermonuclear weapons as the North Koreans have claimed to have. Therefore, instead of being able to build thermonuclear weapons that weigh only 200 kilograms, such weapons may weigh 600 kilograms instead.[52] North Korea's lack of tritium will limit North Korea's ability to MIRV its ballistic missiles and will also limit the types of missiles that North Korea can develop to deliver nuclear weapons to the U.S.

Other Analysts' Estimates of the Size of North Korea's Nuclear Stockpile

How do other analysts' estimates of the North Korean nuclear stockpile compare with mine? I have summarized their estimates in Table 3. Heinonen has not estimated how many nuclear weapons North Korea might have since a variety of weapon designs are possible which could produce a wide range of estimates.[53]

Table 3

Various Estimates of the Size of North Korea's Nuclear Weapon Stockpile End 2023

Estimator	Plutonium (Kilograms)	HEU (Kilograms)	Number of Nuclear Weapons
Heinonen	Not Estimated	~1,000	Not Estimated
Hecker	35 to 68*	~1,100 to ~1,500*	50 to 90*
Albright	63	~2,000**	45 to 73** (113)***
RAND/Asan	45 to 85	~1,900 to ~3,100	103 to 170
This Author	85	1,000 to 1,900	67 to 112

*Author's extrapolation from Hecker's end 2020 estimate
**Author's extrapolation from Albright's end 2022 estimate
***This is the number of nuclear weapons that North Korea could produce if it were to convert all of its nuclear material as estimated by Albright into weapons.

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[52] Ibid., p. 4.

[53] Olli Heinonen, "Development of the Yongbyon Uranium Enrichment Plant Between 2009 and 2021," 38 North, July 16, 2021. https://www.38north.org/2021/07/development-of-the-yongbyon-uranium-enrichment-plant-between-2009-and-2021/

In early 2021 Hecker estimated that at the end of 2020 North Korea could have 20 to 60 nuclear weapons.[54] Since Hecker estimated that North Korea's was producing HEU at a rate of 175 kilograms per year, in three years North Korea would have produced an additional 525 kilograms of HEU. Further the plutonium discharge from the 25 MWt reactor at Yongbyon would have added 10 to 20 kilograms of plutonium to North Korea's stockpile. Therefore, Hecker's estimate of North Korea's nuclear weapon stockpile at the end of 2020 would have grown by about 30 nuclear weapons by the end of 2023, giving North Korea a total stockpile of 50 to 90 nuclear weapons.

In early 2023, Albright estimated that North Korea had 63 kilograms of plutonium and 1,770 kilograms of HEU.[55] In 2023 North Korea did not obtain any additional plutonium but additional HEU production would give North Korea a HEU stockpile of around 2,000 kilograms. In 2023, Albright estimated that North Korea could have a stockpile of 35 to 63 nuclear weapons at the end of 2022. Given North Korea's HEU production in 2023, I have increased Albright's estimate by 10 giving 45 to 73 nuclear weapons by the end of 2023.

Given Albright's large estimate of North Korea's HEU stockpile, his estimate of North Korea's nuclear weapon stockpile is rather low. This is the result of Albright assuming that 30% of North Korea's HEU stockpile is unavailable for nuclear weapons production due to processing losses, sluggish conversion of HEU into weapons, sluggish recovery of HEU from scrap and keeping a large amount of nuclear material in reserve.[56] I consider these assumptions unrealistic given North Korea's stated goal of increasing its nuclear arsenal as rapidly as possible. If one were simply to assume 5 kilograms of plutonium or 20 kilograms of HEU, then given Albright's estimates of North Korea's plutonium and HEU stocks, North Korea could produce 113 nuclear weapons.

RAND/Asan estimated that by the end of 2023 North Korea would have between 103 and 170 nuclear weapons.[57] As I have discussed, the high end of this estimate would require unrealistically large North Korean natural uranium production. The low end of the RAND/Asan estimate is similar to what is implied by Albright's estimates of North Korea's plutonium and HEU stockpiles and is also similar to my high-end estimate.

Future Uncertainties

My estimate that North Korea's nuclear weapon stockpile will grow at a rate of 6 to 11 weapons per year is based on North Korea's current capabilities. But there are a number of ways that North Korea could significantly increase the number of new weapons that it produces each year. As was discussed above, if North Korea's new ELWR is configured to produce plutonium, then

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[54] "Estimating North Korea's Nuclear Stockpiles: An Interview With Siegfried Hecker," 38 North, April 30, 2021. https://www.38north.org/2021/04/estimating-north-koreas-nuclear-stockpiles-an-interview-with-siegfried-hecker/

[55] David Albright, "North Korean Nuclear Weapons Arsenal: New Estimates of its Size and Configuration," Institute for Science and International Security, April 10, 2023, p. 10. https://isis-online.org/uploads/isis-reports/documents/North_Korean_Nuclear_Weapons_Arsenal_New_Estimates_of_its_Size_and_Configuration_April_10_2023.pdf

[56] Ibid., p. 9.

[57] Bruce W. Bennett et. al. "Countering the Risks of North Korean Nuclear Weapons," RAND/Asan, April 2021, pp. 36-37. file:///C:/Users/gjones/Downloads/RAND_PEA1015-1.pdf

it could produce about 20 kilograms of plutonium per year which would increase the rate of North Korea's nuclear weapons production by four per year. North Korea could also continue to build more clandestine centrifuge enrichment plants which could significantly increase North Korea's rate of HEU production. The ELWR configured to produce plutonium and new clandestine centrifuge enrichment plants would probably require more natural uranium than North Korea currently produces. However, over time North Korea might be able to open up new uranium mines which would help to overcome this problem.

Russia is a major wild card. Since Russia's invasion of Crimea in 2014, Russia has been at odds with NATO. Putin would likely be pleased if the U.S. were to be distracted away from Eastern Europe by a growing North Korean nuclear threat. Russia could provide a variety of aid to North Korea to enhance North Korea's nuclear forces. As a major uranium producer, Russia could easily sell/gift North Korea 50 to 100 metric tons of natural uranium to solve any shortage North Korea may have. Russia could provide North Korea with nuclear weapon design information to make it easier for North Korea to produce light-weight high yield thermonuclear weapons which would be capable of being carried by ballistic missiles to strike the U.S. More speculatively, Russia might even provide North Korea with a significant amount of tritium so that it could produce boosted primaries for its thermonuclear weapons. Though some may find the idea of Russia providing significant aid to North Korea's nuclear weapon program farfetched, North Korea's rapid development of a number of different long-range ballistic missiles indicates that Russia may already be aiding North Korea's ballistic missile program.

Conclusions

My estimate of North Korea's nuclear material stockpiles at the end of 2023 is 85 kilograms of plutonium, 1,000 to 1,900 kilograms of HEU and little or no tritium. If converted into the number of weapons, assuming 5 kilograms of plutonium per weapon and 20 kilograms of HEU per weapon results in an estimate of 67 to 112 weapons. Though this uncertainty range is large, it is apparent that North Korea possesses a sizable nuclear arsenal.

I estimate that North Korea's annual HEU production rate is between 110 to 200 kilograms which converts into about 5 to 10 weapons per year. With the Yongbyon reactor producing about one weapon's worth of plutonium per year, based on its current capabilities, North Korea's weapons stockpile would grow at the rate of 6 to 11 weapons per year. If North Korea were to expand its clandestine uranium enrichment capability and/or begin producing large amounts of plutonium from the ELWR, then North Korea's nuclear stockpile could grow at a significantly higher rate.

Russia's actions could up-end these estimates. Given NATO's support of Ukraine in its conflict with Russia, Russia might want to significantly aid North Korea's nuclear program to distract the U.S. from Eastern Europe. This aid might allow North Korea to significantly increase the expansion of its nuclear arsenal and also help North Korea develop more sophisticated deliverable nuclear weapons.

Appendix

Plutonium Production in a Natural Uranium Fueled Graphite Moderated Reactor

Natural uranium can be used to fuel nuclear reactors that use either graphite or heavy water as the moderator. North Korea's 25 MWt plutonium production reactor at Yongbyon uses a graphite moderator. As the uranium is irradiated in the reactor, plutonium is produced in the fuel. At some point the fuel is discharged and can be reprocessed to recover the plutonium. The longer the fuel is left in the reactor the more plutonium it contains. The increase of plutonium in the fuel over time is less than linear since once some plutonium is in the fuel, some atoms can absorb neutrons and either be destroyed by fissioning or converted into Pu-240. If the plutonium is to be used in a weapon, the amount of time that the fuel is left in the reactor is limited so as to reduce the production of the undesirable Pu-240 isotope.

The power that a reactor produces is the energy it generates times the length of time that is operates, which is measured as megawatt-days (MWD). The average burnup of the fuel is the power that the reactor has generated divided by the amount of fuel in the reactor, which in the case of North Korea's reactor is 50 metric tons. The unit of burnup commonly used is megawatt-days per metric ton (MWD/MT).

In the 1940s and 1950s the U.S. built eight graphite moderated, natural uranium fueled plutonium production reactors at Hanford, Washington. In 1959-1960 Hanford conducted 12 test irradiations in two separate reactors, six in the H reactor and six in the KW reactor.[58] The spent fuel was then carefully analyzed to determine its plutonium content. This work showed that the amount of plutonium produced was dependent on the ratio of graphite to uranium fuel in each reactor which is determined by the lattice pitch (the distance between the fuel channels in the reactor). The larger the lattice pitch, the less plutonium is produced. The H reactor had a lattice pitch of 8 3/8 inch (21.3 cm) and the KW reactor had a lattice pitch of 7 ½ inch (19.1 cm). For this work I have averaged the results from the two reactors, which is equivalent to assuming a lattice pitch of 20.2 cm. Later plutonium production reactors had a lattice pitch close to this value and it is likely that North Korea's 25 MWt reactor has a similar lattice pitch.[59]

The averaged Hanford results give a plutonium production of 0.901 grams per MWD at a burnup of 496 MWD/MT and 0.845 grams per MWD at a burnup of 902 MWD/MT. I have linearly extrapolated these values to an initial plutonium production rate of 0.969 grams per MWD at a burnup of 0 MWD/MT. To determine the plutonium produced in North Korea's 25 MWt reactor, I interpolate among these three values depending on the fuel burnup of each discharged batch of North Korean fuel.

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[58] D. W. Hoba and A. D. Vaughn, "Planned Normalization of Plutonium Yield Predictions to the Twelve Two-Ton Test Batch Measurements," HW-69999, General Electric, June 7, 1961, p.7. https://www.osti.gov/servlets/purl/10152151

[59] The three French "G" plutonium production reactors had a lattice pitch of 20.0 cm and the eight British Calder Hall plutonium production reactors had a lattice pitch of 20.3 cm.

While the plutonium production rate depends on the reactor lattice pitch, the Pu 240 content does not. For both the H reactor and KW reactor, at a burnup of 496 MWD/MT, the Pu 240 content is around 4.1% and at a burnup of 902 MWD/MT, the Pu 240 content is around 6.8%.

Even if the burnup of different fuel elements in each batch varies from the average burnup, its plutonium production rate and thus its plutonium content is the same as if all of the fuel had the same burnup as that of the average. This is not the case for the Pu 240 as the fuel with a lower than average burnup has a lower Pu 240 content but also a lower plutonium content. Conversely, fuel with a higher than average burnup has both a higher then Pu 240 content and a higher plutonium content. Therefore, a fuel batch with a wide range of burnups will have a higher Pu 240 content than if all of the fuel had a burnup equal to the average burnup.[60]

This fact is illustrated by the North Korean fuel discharge of its 25 MWt plutonium production reactor from its first cycle. The IAEA has reported that though this fuel had an average burnup of 635 MWD/MT, this batch of fuel had burnups between 64 MWD/MT and 1370 MWD/MT.[61] If all of the fuel had a burnup of the average 635 MWD/MT then its Pu 240 content would have been about 5.0%. However, I have calculated, by looking at each burnup grouping of the spent fuel separately, that the actual Pu 240 content was around 6.0%.[62]

The other batches of fuel discharged from the 25 MWt reactor at Yongbyon have a lower burnup and therefore a lower Pu 240 content. I estimate that the rest of the plutonium produced at Yongbyon has a content between 3% and 4.5% Pu 240.

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[60] R. Augier De Cremiers, "Les Solutions Mecanographques Es Apportees Par Marcoule Aux Problems De Programmation De Dechargement En Marche Des Reacteurs," *Operating Experience with Power Reactors*, Volume II, International Atomic Energy Agency, Vienna, 1963, p. 339, figure 1. https://www.osti.gov/etdeweb/servlets/purl/22108181

[61] David Albright and Paul Brannan, "The North Korean Plutonium Stock, February 2007," *Institute for Science and International Security*, February 20, 2007, p. 4. https://www.isis-online.org/publications/dprk/DPRKplutoniumFEB.pdf

[62] Grouping provided in: "ISIS Course: Introduction to Reactors and Fuel Cycle: Small Yongbyon Nuclear Reactor," Institute for Science and International Security, October 16, 2014. https://isis-online.org/uploads/conferences/audio-video/Yongbyon_reactor_and_fuel_cycle_october_16_2014_-_3-2.pdf