# North Korea's Stockpiles of Fissile Material

*Siegfried S. Hecker**
*Chaim Braun***
*Chris Lawrence****

North Korea has conducted five nuclear tests and is believed to be rapidly increasing the size and sophistication of its nuclear arsenal. Increased sophistication, particularly the ability to miniaturize nuclear devices, requires more nuclear tests. The size of the arsenal is limited primarily by the stockpile of fissile material — plutonium and highly enriched uranium (HEU). Current plutonium inventories are estimated with moderate confidence to be in the range of 20 to 40 kg, sufficient for the manufacture of 4 to 8 plutonium bombs. HEU inventories are estimated with much greater uncertainty to be in the range of 200 to 450 kg, sufficient for 10 to 25 HEU bombs. Annual production rates are estimated to be less than 6 kg of plutonium and ~150 kg HEU.

**Key Words:** North Korea, fissile material, nuclear weapons, plutonium, highly enriched uranium (HEU), tritium, fuel cycle

---

* Siegfried Hecker is research professor and senior fellow at Center of International Security and Cooperation, Stanford University and emeritus director of the Los Alamos National Laboratory. He has visited North Korea seven times between 2004 and 2010. Email: shecker@stanford.edu

** Chaim Braun is an affiliate at the Center of International Security and Cooperation, Stanford University. He has more than forty years experience in nuclear energy and fuel-cycle issues in research, industrial and academic institutions.

*** Chris Lawrence is a research fellow with the Program on Science, Technology and Society in Harvard's Kennedy School of Government. He is a nuclear scientist by training, and is generally interested in questions of knowledge as they pertain to arms control and disarmament.

KOREA OBSERVER, Vol. 47, No. 4, Winter 2016, pp. 721-749.

## I. Introduction

On September 9, 2016, seismic stations around the world picked up the unmistakable signals of a North Korean underground nuclear test in the vicinity of Punggye-ri. It was the second successful nuclear test in 2016 and believed to be the fifth nuclear test since the initial test on October 9, 2006. These tests suggest an increasingly sophisticated North Korean nuclear arsenal. The size of the arsenal is likely constrained by the stockpile of fissile materials, namely plutonium and highly enriched uranium (HEU), for bomb fuel. Accurately estimating the size of North Korea's fissile materials stockpile is essential to understanding the status of its nuclear weapon program and the threat it poses.

Plutonium is produced in nuclear reactors. The quantity and quality of plutonium depends on reactor design and operations. Estimates of North Korea's plutonium stockpile can be made reasonably accurately because much is known about the North Korean reactors and operation of the reactors is readily discernable from satellite imagery. Natural uranium contains only 0.72 percent of the fissile isotope Uranium-235, the rest is Uranium-238. Hence, natural uranium must be enriched, or concentrated in U-235. Of the numerous technologies available, North Korea has chosen centrifuge enrichment, which has also become the method of choice for established nuclear weapons and nuclear energy states. HEU estimates have great uncertainties because centrifuge enrichment facilities have a small physical footprint and are easy to conceal. In this article, we provide estimates of North Korea's stockpiles of plutonium and HEU by examining in detail North Korea's means of production of these materials. We explain the methodology we used to make the stockpile estimates. We also briefly examine North Korea's potential for tritium production because on January 6, 2016, Pyongyang claimed to have tested a hydrogen bomb, which requires tritium for fusion.[1]

1. Hecker concluded that this test was unlikely a test of a modern, two-stage thermonuclear device, typically called a hydrogen bomb. See Siegfried S. Hecker,

## II. Plutonium Production and Inventories

### A. The 5 Megawatt-electric Reactor (5 MWe)

North Korea has operated the 5 megawatt-electric reactor (5 MWe) at the Yongbyon Nuclear Center shown in Figure 1 since 1986.[2] This reactor is believed to have produced North Korea's entire inventory of plutonium. The 5 MWe reactor is a gas-cooled, graphite-moderated reactor (GCR) that uses natural-uranium metallic fuel, clad in an magnesium-aluminum alloy. The reactor was originally intended as a pilot reactor in preparation for the larger 50 MWe and 200 MWe reactors that were partially constructed at the time the Agreed Framework[3] was implemented in 1994. The magnesium-clad fuel elements corrode when stored in water and, therefore, must eventually be reprocessed. Under optimal conditions, the 5 MWe reactor operates for about two to three years producing ~6 kg of plutonium per year before its entire core load is discharged and replaced with a new natural uranium fuel rods. The discharged or spent fuel is cooled in a water pool next to the reactor building for several months before it is transferred to the Radiochemical Laboratory (RCL) for reprocessing.

Most of what was known about the layout and technical characteristics of the reactor before the Agreed Framework is derived from North Korea's 1992 declaration to the IAEA and from the follow-on

---

"What to Make of North Korea's Latest Nuclear Test?" *38 North* (September 12, 2016), ([http://38north.org/2016/09/shecker091216/]).

2. The reactor is described in detail in David Albright and Kevin O'Neill, eds., *Solving the North Korean Nuclear Puzzle* (Washington, D.C.: Institute of Science and International Security, November 2000). Reactor operations are updated in Chaim Braun et al., North Korean Nuclear Facilities After the Agreed Framework (Stanford, CA; Center for International Security and Cooperation, 2016), ([http://cisac.fsi.stanford.edu/publication/north-korean-nuclear-facilities-after-agreed-framework]).
3. The Agreed Framework signed between the United States and North Korea on October 21, 1994 in Geneva agreed to have North Korea freeze its existing nuclear program. In addition to U.S. supply of light water reactors and delivery of heavy fuel oil, the two sides agreed to move to work toward full normalization of political and economic relations.

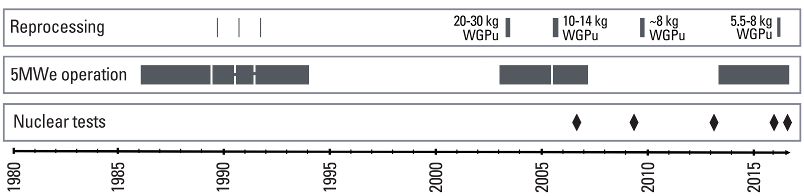
IAEA visit for verification.[4] The original thermal capacity was believed to be 20 MWth, with an electrical output of 5 MWe, although during the January 2004 visit to the Yongbyon Nuclear Center by one of the authors (Hecker), Director Ri Hong-sop told him that the reactor was designed for 25 MWth.[5] This visit confirmed that the reactor had been brought back into operation in spite of having been in a stand-by mode for eight years during the Agreed Framework freeze.

*Figure 1. 5 MWe Reactor at Yongbyon (S.S. Hecker)*

4. Albright and O'Neill, *Solving the North Korean Nuclear Puzzle*.
5. *An Update on North Korean Nuclear Developments, Day 2, Hearings Before the Senate Committee on Foreign Relations*, 108th Cong., 2nd sess., (2004) (statement of Siegfried S. Hecker, Senior Fellow, Los Alamos National Laboratory), ([fas.org/irp/congress/2004_hr/012104hecker.pdf]).

A timeline of estimated 5 MWe reactor operations is shown in Figure 2. The reactor began operations in 1986 and was run until the beginning of the Agreed Framework in 1994, which resulted in the shutdown of the reactor until the demise of the Agreed Framework at the end of 2002.[6] The reactor was restarted in January 2003, unloaded in 2005 to remove the spent fuel to extract plutonium, refueled and restarted. In July 2007, operations were suspended as a result of the February 2007 six-party agreement to disable the Yongbyon nuclear facilities. The spent fuel was not reprocessed until after the breakdown of the six-party talks in spring of 2009.

*Figure 2. Timeline of Reactor Operations and Reprocessing Campaigns in Yongbyon*[7]




The reactor had not been restarted by the time of Hecker's seventh visit to North Korea in November 2010. However, much preparatory work had been done. One of the most important was to replace the reactor's cooling tower that North Korea destroyed in June 2008 as a gesture of good faith (and also in return for financial remuneration from Washington) during the disablement phase of diplomacy. There

6. See Siegfried S. Hecker, "Lessons Learned from the North Korean Nuclear Crises," *Daedalus*, Vol. 139, No. 1 (Winter 2010), pp. 44-56, for details of the Agreed Framework, its demise and how it affected the Yongbyon nuclear complex.
7. Judging from the burn-up times of the spent fuel, it is likely that all of the plutonium produced in the 5 MWe reactor over the years is of weapons grade (WGPu) — that is it contains more than 93% of the isotope Pu-239 (or less than 7% Pu-240). Based on discussion in Yongbyon and with several of the outside technical experts who have visited Yongbyon, Hecker came to the same conclusion. In fact, some of the campaigns may have yielded plutonium with even greater Pu-239 content.

was considerable speculation by outside technical experts that it was not restarted because it had reached end of life. When Hecker probed the chief engineer about this possibility during the 2010 visit, the chief engineer smiled and stated that the same community believed that North Korea would never be able to restart the reactor after the 1994 to 2002 freeze of operations. He said that they restarted it then, and will also be able to do so again once they decide they need it. And, so they did in August 2013. By that time, they had developed a cooling system using the Kuryong River for a supply of cooling water and for discharge of hot water from the reactor.[8] That system depends on a pump house that was built as a part of the ELWR construction and was completed only in early 2013. Evidently the pumping capacity installed could also serve the cooling requirements of the 5 MWe reactor. As shown in Figure 2, the reactor has operated since August 2013, albeit intermittently, with several interruptions caused by cooling problems, mostly associated with the supply of adequate river water. There was also a shutdown in late 2015 for defueling and refueling the reactor.

North Korea has demonstrated an impressive capability to keep the 5 MWe reactor operational. In addition to having to make up for the loss of the cooling tower, it had to fabricate new fuel elements in spite of having disabled much of the metal fuel fabrication line as part of the 2007 six-party agreement and the fact that it reconstructed in its place an entirely renovated building in 2009-2010 to house the new Yongbyon centrifuge facility. Hence, based on 30 years of reactor and fuel fabrication experience and the resilience demonstrated by the Yongbyon technical teams, we believe that North Korea will be able to keep the 5 MWe reactor operating at least for another decade and perhaps longer. Reactor operation will also not be constrained by uranium fuel because North Korea is believed to have ample uranium ore resources, large enough not only for weapons use, but also for nuclear power reactors which require significantly more fuel.[9]

---

8. The efforts to rebuild a cooling system using the river is described in detail by Braun et al., *North Korean Nuclear Facilities*.

### B. The Back End of the Fuel Cycle — Plutonium Reprocessing

The Radiochemical Laboratory (RCL) at Yongbyon is a fully functional reprocessing plant with a design capacity far exceeding that required to reprocess the entire core of spent fuel from the 5 MWe reactor.[10] It employs a modified version of the PUREX (Pu-U Redox Extraction) process. In a dedicated nuclear energy program based on such reactors, plutonium from reprocessed spent fuel is stored in the form of plutonium dioxide (PuO2) since this form is easy to store and may be useful for fuel recycling in reactors, or other energy applications. In a weapons program, a further step is carried out to convert the PuO2 into plutonium metal for weaponization. Whereas North Korea had denied having produced plutonium metal before 2000,[11] Yongbyon director Ri Hong-sop showed a 200-gram piece of plutonium metal to Hecker during the 2004 visit. In August 2007 Hecker was shown the plutonium laboratory in Yongbyon in which plutonium metal is processed through the alloying stage. Director Ri told Hecker that it is then sent off site to weapon component fabrication.

Most of what we know about the RCL was obtained from pre-Agreed Framework North Korean declarations to the IAEA, which were subsequently verified.[12] IAEA inspectors had access to the RCL, which was in stand-by status for the duration of the Agreed Framework (1994-2002). The facility was reopened in 2003 after the demise of the Agreed Framework to enable the reprocessing campaign to extract plutonium from the 8,000 spent fuel rods that had been in the storage pool since 1994 under IAEA monitoring. Upgrades to the

---

9. Andrea Berger, "What lies beneath: North Korea's uranium deposits," *NK News.Org* (August 28th, 2014), ([https://www.nknews.org/2014/08/what-lies-beneath-north-koreas-uranium-deposits/]). One of the authors (Hecker) received independent confirmation of significant uranium resources in North Korea in conversation with a Russian academician who served on Soviet uranium geological survey teams in North Korea in the 1950s.
10. Details of the facility are described in Albright and O'Neill, *Solving the North Korean Nuclear Puzzle*; Braun et al., *North Korean Nuclear Facilities*.
11. Albright and O'Neill, *Solving the North Korean Nuclear Puzzle*.
12. Ibid.

facility were made subsequently as described by Hecker based on his 2004, 2007 and 2008 visits.[13] These upgrades increased the capacity of the RCL by 30 percent, but more importantly improved the efficiency of plutonium extraction.

In 2007 and 2008, North Korea took numerous steps to disable, but not dismantle, a number of operations in the RCL as described by Hecker as a result of the six-party disablement agreement.[14] Much as was the case for the 5 MWe reactor, North Korea was able to reverse these steps and bring the facility back into operation for a reprocessing campaign in 2009. No outsiders have had access to the RCL since, but based on information gained from overhead satellite imagery, it was apparent that North Korea conducted a subsequent reprocessing campaign in the spring of 2016.[15] Our estimates of the conduct of various reprocessing campaigns are shown in Figure 2. It is highly unlikely that North Korea has an additional reprocessing facility aside from the small hot cells at the IRT-2000 reactor complex. Hence, the reprocessing campaigns give an accurate estimate of the amount of plutonium extracted to date, as will be discussed below. The RCL appears to be in good working order and capable of continued operation for some time so that it will likely not be a limiting factor in plutonium production.

### *C. Other Potential Sources of Plutonium*

North Korea agreed to freeze the construction of the two larger gas-cooled reactors, the 50 MWe at Yongbyon and 200 MWe at Taechon as part of the Agreed Framework. These reactors would almost cer-

---

13. The details of the status of the RCL are provided by Braun et al., *North Korean Nuclear Facilities*.
14. Siegfried S. Hecker, *North Korea's Yongbyon Nuclear Complex: A Report by Siegfried S. Hecker* (Stanford, CA: Center for International Security and Cooperation, 2010), ([cisac.stanford.edu/publications/north_koreas_yongbyon_nuclear_complex_a_report_by_siegfried_s_hecker]).
15. *Application of Safeguards in the Democratic People's Republic of Korea*, report by the Director General, International Atomic Energy Agency, August 19, 2016.

tainly have been completed by the time the Agreed Framework was terminated at the end of 2002, but instead they were not salvageable and have since been completely scrapped. Although North Korea quite clearly pursued a secret enrichment effort during the Agreed Framework, the fact that North Korea sacrificed a combined capacity of producing approximately 300 kg plutonium per year remains one of the most important and often overlooked successes of the Agreed Framework.[16]

The only other potential source of plutonium is the Russian-supplied IRT-2000, a small research reactor. Its primary function was research, training and medical isotope production. It has been run sparingly since 1992 when Russia no longer supplied North Korea with the HEU fuel necessary for the reactor. Dreicer[17] computed the potential plutonium production in the reactor over its lifetime and concluded that at most it could have produced 4 kg of plutonium. However, based on Hecker's discussion with Yongbyon technical experts, we doubt that even that much plutonium was produced in the IRT-2000 reactor. For the purpose of this analysis we assume zero is reasonable. We also believe it unlikely that North Korea received plutonium or was able to buy plutonium from other countries at any time.

The new experimental light water reactor (ELWR) under construction at Yongbyon is a potential future source of plutonium. Hecker and the Stanford University delegation were shown the very beginning of that construction during their November 2010 visit. Hecker was told that the reactor is designed for a power level of 100 MWth (roughly 25 to 30 MWe) as a prototype for future larger power reactors.[18] The exterior of the reactor plant appears to be complete, but the reactor has not yet become operational. When it does, it will produce roughly 10 to 15 kg of plutonium annually, but if operated in a mode optimized for electricity production, it will produce reactor-

16. Hecker, "Lessons Learned."
17. Jared S. Dreicer, "How Much Plutonium Could Have Been Produced in the DPRK IRT Reactor?" *Science & Global Security*, Vol. 8, No. 3 (2000), pp. 273-286.
18. Hecker, *North Korea's Yongbyon Nuclear Complex*.

grade, rather than weapon-grade plutonium. The high levels of heavier plutonium isotopes in reactor-grade plutonium make it less than ideal, but not impossible, for weapons use.[19] However, the reactor could be operated in a short burn-cycle mode to reduce the undesirable heavy isotopes. Moreover, as Albright[20] points out, the reactor can be configured specifically to produce significant quantities of weapon-grade plutonium. We have no direct knowledge of what North Korea's plans are for the ELWR; however, at this point future power generation looks likely.

### *D. Plutonium Inventories*

The amount of plutonium produced can be estimated from the reactor design and fuel characteristics, the reactor power level during operation, and the duration of reactor operation. The reactor design and fuel characteristics are well known from the various visits and inspections of the nuclear complex. The duration of reactor operation has been closely monitored by overhead satellite imagery. The telltale signs of operation were the steam plumes from the cooling tower during the early years and hot effluent discharges into the Kuryong River in recent years. Although, the reactor power level estimates are less robust, it has been possible to make reasonably accurate estimates of the amount of plutonium that North Korea has produced in the 5 MWe reactor over the past 30 years.

Operation of the RCL for reprocessing can also be estimated reasonably well by observing thermal signatures of the facility, operations of the supporting power plant and vehicle movements to and from the plant. Moreover, IAEA inspectors, U.S. technical teams and Hecker had detailed access to the RCL over the years. Determining the efficiency of the reprocessing operation and estimating the

---

19. Carson Mark, "Explosive Properties of a Reactor-Grade Plutonium," *Science & Global Security*, Vol. 4 (1993), pp. 111-118, ([http://scienceandglobalsecurity.org/archive/sgs04mark.pdf]).
20. David Albright, *North Korean Plutonium and Weapon-Grade Uranium Inventories* (Washington, D.C.: Institute for Science and International Security, 2015).

amount of plutonium remnant in the processing waste stream and holdup in the plant's equipment are more difficult. We estimate scrap and holdup to be roughly 10 percent during reprocessing. There may be an additional 10 percent scrap in plutonium metal and component fabrication taking into account that North Korea will likely recycle production residues to extract as much plutonium possible.

The best estimates of plutonium produced based on 5 MWe reactor operation from 1986 to the end of 2015 as illustrated in Figure 2 are shown in Table 1. We estimate this to be in the range of 42 to 63 kg. Assuming a 10 percent loss during reprocessing reduces the estimates to 37.8 to 56.7 kg. If it is further assumed that three of the five nuclear tests used plutonium[21] with production losses in plutonium purification and metal fabrication of 10 percent, then North Korea is estimated to have a current plutonium inventory of 21.3 to 39.6 kg, which we

*Table 1. Estimated Plutonium Production in the Yongbyon Nuclear Complex*

| Operation and shutdown | Residence; avg. burnup | Amount. spent fuel removed | Reprocess duration | Separated WG Pu | Data/reasoning |
|---|---|---|---|---|---|
| Op. 1986-1989 Shutdown 1989 (70-100 days) | 3 years; unknown | Unknown | Unknown | Less than 2 kg, possibly <100g | Satellite imagery; information from Calder Hall reactors (Albright et al. 2000) |
| Op. 1989-1994 Shutdown 1994 | Unknown; ~650 MWth-d/t | Full core; 8,000 elem.; 50 tons U | January-June 2003 | 20-30 kg | IAEA statements on shutdown duration; Ri Hong Sop comment in 2004 |
| Op. 2003-2005 Shutdown 2005 (-70 days) | 2 years; 330 MWth-d/t | Full core | June-December 2005 | 10-14 kg | Ri comment 2004; satellite imagery for reactor operations |
| Op. 2005-2007 Shutdown July 2007 | 1+ years; <200 MWth-d/t | Full core | 2009 | ~8 kg | Satellite imagery |
| Op. 2013-2015 Shutdown 2015 | 2 years intermittent: uncertain burnup | Likely full core | 2016 | 5.5-8 kg | Albright et al.[22] |
| Op. 2016 | In reactor | | | | |

round off to 20 to 40 kg.

The actual uncertainty is even greater than this range because we have no information about the nature of North Korea's bomb design, what kind of devices were tested, and how much plutonium or HEU were used. Since all testing has been underground and generally well contained, it has not been possible to discern what fissile materials were used in the test devices. The only information available is that Director Ri Hong-sop told Hecker during the 2007 visit that the first device used plutonium.

Albright and colleagues have estimated plutonium inventories to be in the range of 35.5 to 42 kg by September 2016.[23] The difference from our estimates stems primarily from the uncertainty of how much plutonium North Korea may have produced prior to 1992 and how much plutonium was expended in North Korea's nuclear tests. We consider the agreement to be quite good considering the overall uncertainties. In particular, the upper range of both estimates agree quite well, thus placing a reasonable upper bound on the estimate of plutonium available for weapons. The North Korean government has also issued various declarations over the years. In 2008, Hecker was told by North Korean officials that they possessed an inventory of 30 kg of plutonium, which we interpreted as separated plutonium. Considering that North Korea also possessed an additional roughly 8 kg

21. We have no direct confirmation of how many of the test devices used plutonium. Our assumption is based on the rationale that if the first two tests used plutonium, it would be imperative to get one more result with plutonium to test design assumptions. By 2013, however, additional plutonium tests would quickly deplete the inventory leaving little for a nuclear arsenal. This is also the time by which the Yongbyon centrifuge facility could have been in operation for sufficient time to assure a future supply of HEU, thus the likely switch to HEU test devices.
22. David Albright and Serena Kelleher-Vergantini, *Plutonium, Tritium, and Highly Enriched Uranium Production at the Yongbyon Nuclear Site* (Washington, D.C.: Institute for Science and International Security, 2016).
23. David Albright et al., *September 2016: Monitoring Activities at the Yongbyon Nuclear Site* (Washington, D.C.: Institute for Science and International Security, 2016), ([http://isis-online.org/uploads/isis-reports/documents/Sept_2016_Yongbyon_Update_20Sept2016_Final.pdf]).

of plutonium in spent fuel that had not yet been reprocessed at that time, and the additional 5.5 to 8 kg reprocessed in 2016, places the North Korean statement near the middle of our estimates.

## III. Highly Enriched Uranium Production and Inventories

Estimates of highly enriched uranium inventories have enormous uncertainties compared to plutonium estimates. The principal facilities for plutonium production, namely the Fuel Fabrication Facility, the 5 MWe reactor and the RCL have been open for inspection off and on for nearly 25 years, both to IAEA inspectors and U.S. technical teams. Hecker visited these facilities four times between 2004 and 2010 and had extensive technical discussions with Yongbyon nuclear specialists. Although no outsiders have been at the Yongbyon facilities since 2010, the reactor sites are constantly monitored by government and private-sector satellite imagery enabling the well-bounded estimates presented above.

Unlike reactor operations, centrifuge enrichment facilities are virtually undetectable from outside the country. Moreover, the outside world has had only one direct observation of a North Korean centrifuge facility — namely during Hecker's visit in 2010. As described by Hecker,[24] it was only a glimpse in that he and the Stanford delegation were given limited access and rushed through the newly constructed facility. They were not even able to verify that the facility was actually operating at the time. We also note that the centrifuge plant was constructed in the Fuel Fabrication Facility by stripping and renovating Building 4, which until early 2009 housed the metal fuel-rod fabrication plant for the 5 MWe reactor. The centrifuge plant shown to Hecker and colleagues in November 2010 was, as far as we know, not detected by anyone outside North Korea prior to this visit.

The small-industrial-scale centrifuge facility contained 2,000 centrifuges, ancillary equipment and a modern control room. The delega-

24. Hecker, *North Korea's Yongbyon Nuclear Complex*.

tion was only able to view the centrifuge hall through windows from an observation deck above the hall. Only the external smooth aluminum casings (without external cooling coils) and the piping for the uranium hexafluoride gas were visible. The general configuration of the centrifuges appeared to resemble the Pakistani P-2 model, which is a supercritical centrifuge based on Urenco's G-2 centrifuge model. The chief engineer who guided the 2010 tour indicated that they were indigenously produced, but resemble those at Urenco's Almelo facility, which contains G-2 centrifuges (supporting the resemblance to P-2 centrifuges). He further indicated that their centrifuges were not P-1 centrifuges, which use aluminum alloy rotors and have about one fourth the capacity of the P-2s. He stated that each rotor was divided into two equal sections connected by a single bellows. The chief engineer was not willing to provide the delegation with detailed dimension or design information.

The limited information given was consistent with visual inspection by the delegation. When asked about the materials for the centrifuge rotor, the chief engineer indicated that they were of an alloy containing iron, and this implies maraging steel rotors (also consistent with P-2 designs). We assumed that this is likely to be Grade 350 maraging steel, which is typical for G-2 and P-2 rotors. However, it is doubtful that North Korea has the capacity to produce this grade of maraging steel because very sophisticated and specialized equipment and process controls are required to produce it. Although it is believed that North Korea imported some quantities of Grade 350 maraging steel, it may also be augmenting that with domestically produced Grade 250 maraging steel, which is considerably easier to produce.[25]

The chief engineer indicated that the facility had been completed shortly prior to the visit, and that during the visit it was enriching uranium to levels of 3.5% U-235 (with a range of 2.2 to 4%) to provide fuel for the new ELWR under construction. It was not possible for

25. John Bistline et al, "A Bayesian Model to Assess the Size of North Korea's Uranium Enrichment Program," *Science & Global Security*, Vol. 23, No. 2 (2015), pp. 71-100.

the delegation to verify these claims. In addition, he stated the facility had an enrichment capacity of 8,000 kg-SWU[26]/year, or about 4 kg-SWU/year per machine. If accurate, this capacity would be enough to produce 2 tons of approximately 3.5% low enriched uranium (LEU), which is consistent with the stated requirements of the ELWR, the core of which Hecker was told would contain 4 tons of uranium oxide fuel. The same capacity could produce roughly 40 kg of highly enriched uranium (HEU) (90% U-235) per year if the facility were configured to produce HEU, which is certainly possible, but unlikely at the time the delegation was there.

Hence, all estimates of North Korea's enrichment capacity at Yongbyon are based on Hecker's report of the visit and depend heavily on the veracity of the chief engineer's description of the facility. The rest of our knowledge about North Korean centrifuge capacity is obtained only through indirect and circumstantial evidence.

One of the most important questions is whether or not North Korea has additional covert centrifuge facilities, either at Yongbyon or elsewhere. The existence of a centrifuge enrichment program was highly contested before the 2010 visit. Hecker's North Korean hosts officially denied the existence of such a program during his six previous visits. Hecker, however, was convinced that an enrichment program existed based on discussions with some North Korean officials and on the revelations of former Pakistani president Pervez Musharraf. In his book[27] Musharraf stated that A.Q. Khan supplied a starter kit of roughly two-dozen centrifuges to North Korea and trained North Korean technical specialists at Pakistan's Khan Research Laboratory's centrifuge facility. Nevertheless, Hecker was shocked by the size and sophistication of the modern, small-industrial-scale enrichment facility that the North Koreans revealed in November 2010.

During that visit, Vice Minister Ri Yong-ho told the delegation that Pyongyang had decided to repurpose the Yongbyon Nuclear

---

26. SWU — separative work unit stands for the effort necessary to separate U-235 and U-238. It is measured in kilograms of separative work (kg SW).
27. Pervez Musharraf, *In the Line of Fire: A Memoir* (New York: Free Press, 2006).

Center from plutonium production to build an indigenous experimental light water reactor (ELWR), which in turn, necessitated developing uranium enrichment capabilities to make LEU reactor fuel. He told Hecker that no one including Hecker believed that when in September 2009, when North Korean officials announced having been successful in enriching uranium.[28] This was North Korea's first definitive admission that it pursued uranium enrichment. However, judging from the scale and sophistication of the facility revealed in 2010 and knowing that it had been constructed in less than two years, we conclude that an enrichment program must have been in existence before that visit. In fact, to be able to install 2,000 centrifuges with all ancillary equipment and controls and get it to the stage that the Stanford delegation witnessed in 2010, North Korea must have operated a similar pilot facility of sufficient size for several years.[29] Although the evidence is indirect, we find it indisputable that North Korea has a covert centrifuge facility, and it likely operated such a facility for at least several years before 2010. Since a centrifuge facility footprint is so small, it is not surprising that such a facility has not yet been identified by overhead satellite imagery.

At Yongbyon, however, there were many signs of an expanding nuclear program, particularly at the fuel fabrication complex. Some of that construction is likely associated with fuel fabrication for the EWLR, but is believed to support a growing uranium enrichment program. For example, in late 2013, the building housing the centrifuge facility was expanded by an additional 14-meter-wide section along the entire -100-meter length of the original building. It is not clear how many centrifuges, if any, had been added to this additional floor

28. In a September 4, 2009 letter to the President of the UN Security Council, the North Korean permanent representative to the United Nations stated that North Korea's "experimental uranium enrichment has successfully been conducted to enter into completion phase" ("DPRK Permanent Representative Sends Letter to President of UNSC," KCNA, September 4, 2009). This announcement followed Pyongyang's earlier announcement that it will develop its own LWR reactor.
29. We estimate that the covert facility likely had roughly 330 to 660, operating elsewhere. In order to study intra- and inter-cascade dynamics, such a pilot plant would need to contain at least two cascades, or at least 660 centrifuges.

*Figure 3. North Korea's Uranium Centrifuge Facility (blue roof) in 2010 (Left) and after being Expanded in 2013 (Right)*

* Images from Google Earth, 2/17/2007 and 9/24/2014; CR 2015 DigitalGlobe.

space since it was not possible to see inside. Figure 3 shows the centrifuge facility as it existed during Hecker's visit in 2010 and the 2013 expansion as viewed in 2014. That expansion likely doubled the centrifuge capacity.

One additional and somewhat surprising look inside the North Korean nuclear complex comes from information posted by the Korean Central News Agency (KCNA) to highlight the supreme leader's visits around the country. During Kim Jong-il's rule, he was seen to visit industrial facilities that housed flow-forming machines, which are essential to the production of centrifuge rotors. In fact, over the years, three generations of such machines were shown.[30] In addition, Kim Jong-il also visited a fabrication shop that showed what may have been preforms for centrifuge rotors. Kim Jong-un continued his father's tradition and has been seen at the sites of many missile launches as well as in a factory that apparently manufactured missiles. Most remarkably, he was shown with a mockup of what KCNA claimed to be a miniaturized nuclear warhead.[31] However, we are not aware of any other Kim Jong-un visits that revealed additional details

30. R. Scott Kemp, "Is This Where North Korea Makes Its Centrifuges?" *Arms Control Wonk* (June 24, 2013), ([http://www.armscontrolwonk.com/archive/206637/is-this-where-north-korea-makes-its-centrifuges/]).
31. Jeffrey Lewis, "Five Things You Need to Know about Kim Jong Un's Photo Op with the Bomb," *38 North* (March 11, 2016), ([http://38north.org/2016/03/jlewis031116/]).

about the centrifuge program.[32]

In Braun et al.[33] we presented our best estimates on the North Korean centrifuge program. The results are reproduced in Table 2. Nearly all of the technical information is drawn from statements made during the Stanford visit by the facility's chief engineer (CE).

*Table 2. Estimated Properties of the Uranium Enrichment Facility at Yongbyon*

| Property | Estimate | Data / reasoning |
|---|---|---|
| Number of centrifuges | ~2000 | CE comments to Hecker in 2010; consistent with visual inspection |
| Cascade layout | 6 x 330-centrifuge cascades | CE comments; consistent with visual inspection; consistent with Pakistani practice |
| Stated facility enrichment capacity | 8,000 kg-SWU / year | CE comments; slightly lower than G-2 performance ratings under optimal performance |
| Centrifuge type | P-2 type; supercritical centrifuge | CE comments; resemblance to G-2; known collaboration with A.Q. Kahn |
| Rotor material | Maraging steel (grade unknown) | CE comment - "alloy containing iron" |
| Casing material | Aluminum (likely 6061-T6) | CE comment; consistent with visual inspection; |
| Approx. centrifuge dimensions | 20cm dia.; < 180cm length; (may have been 150cm with pedestal) | CE comment; consistent with visual inspection |
| Bellows arrangement | Single bellows | CE comment; consistent P-2 and G-2 models |
| Enrichment rate per centrifuge | 4 kg-SWU / year | CE comment; slightly lower than G-2 performance ratings under optimal performance |
| Stated enrichment level | Average 3.5 % U-235 product (2.2-4% across core); 0.27% U-235 tails | CE comment; consistent with fuel for LWR |

32. It is interesting to note that no visits of the leaders to the Yongbyon Nuclear Complex have ever been shown. In fact, it is quite likely that the leaders have never been at the nuclear complex. That is what Hecker was told during his visits to Yongbyon.

33. Braun et al., *North Korean Nuclear Facilities*.

We do not know how many centrifuges North Korea might possess beyond those observed by the Stanford delegation in 2010. As indicated above, the size of the Yongbyon facility has been doubled since that time and North Korea almost certainly has a covert centrifuge facility, likely located off site, in which it likely tested the centrifuge configuration before installing the one revealed at Yongbyon in 2010. We suspect that North Korea installed new centrifuges in the Yongbyon facility leaving the covert facility for additional research and/or to further enrich LEU that was initially produced at Yongbyon. Whether or not it has an additional production-scale facility is also not known.

We are also uncertain about what enriched uranium products are produced in the various centrifuge facilities. The Stanford delegation was told in 2010 that the facility was producing LEU to fuel the ELWR that was just beginning construction at the time. Construction progress monitored with overhead satellite imagery showed that most of the exterior of the plant was completed by the end of 2013. Additional facilities consistent with electricity production have been observed since, but the reactor is not operational as of December 2016. It is quite possible that producing the oxide fuel and cladding, which are very different from the metallic fuel and cladding used in the 5 MWe reactor, is proving somewhat more challenging than anticipated. Nevertheless, it is reasonable to assume that the Yongbyon plant produced sufficient LEU to be able to supply the first core and a few fuel reloads for the ELWR. North Korea could have produced enough LEU for the initial core and up to 2.5 full reloads of fuel for the ELWR by the end of 2015.

It is possible that the recently expanded centrifuge facility in Yongbyon takes LEU from the original plant and increases enrichment levels up to weapons grade, which is typically 90 percent U-235. The addition could also produce LEU in a mode in which Yongbyon produces only LEU, which is then sent off site to a "topping" enrichment plant to increase enrichment levels to weapon grade. Any of these scenarios are easily within reach since they require no new technical innovations. Tracking of uranium hexafluoride cylinder shipments in and out of the Yongbyon fuel complex might provide some insight to resolve these questions.

## A. Estimating HEU Production and Inventories

Several authors have published estimates of HEU production in North Korea. The most widely cited study was conducted by David Albright.[34] Albright made three estimates by assuming different levels of capability, with a high estimate of 48,000-58,000 kg-SWU/year by 2020. Bistline et al.[35] attempted to constrain uncertainty of the possible production rate by considering limited supply of critical materials required for centrifuge construction. Through expert elicitation, they predicted that supply of maraging steel, high-strength aluminum, and pivot bearings would be the main bottlenecks on the expansion of enrichment capacity. Bistline et al. utilized optimization and Monte Carlo tools to derive a probability distribution for enrichment capacity, which spanned a large range consistent with the uncertainties of North Korea's capabilities. The capacity was based on expert judgment of the potential import of the key materials from different countries and the probability of domestic production of 250 Grade maraging steel for rotors.[36] The most likely capacity was estimated to be 35,000 kg-SWU/year by 2015. Braun[37] made two separate estimates based on what we know and surmise about North Korean centrifuge capabilities and schedule limitations in bringing such capabilities on line. These are described in Braun et al. and summarized in Table 3.

The above estimates of enrichment capacity can be utilized to derive an estimate for the stockpile of HEU potentially available for

34. David Albright, "Future Directions in the DPRK's Nuclear Weapons Program: Three Scenarios for 2020," *U.S.-Korea Institute at SAIS* (February 2015), ([http://38north.org/wp-content/uploads/2015/02/NKNF-Future-Directions-2020-Albright-0215.pdf]).
35. Bistline et al. "A Bayesian Model."
36. As described in Bistline et al. (Ibid), it is assumed North Korea had to import 350 grade maraging steel, but judged with high probability to be able to produce 250 grade maraging steel with about a 20 % loss of enrichment capacity.
37. Braun et al., *North Korean Nuclear Facilities*.

*Table 3. Summary of Estimates for North Korea's Enrichment Capacity*

| Author(s) | Assumptions | Estimated current centrifuge numbers | Estimated total enrichment capacity by 2014 | Projected total enrichment capacity by 2020 |
|---|---|---|---|---|
| Albright et al. | • Numerous technical and economic constraints (low estimate) | P-2: 2,000 | 8,000 kg-SWU /yr | 12,000-16,000 kg-SWU /yr |
| | • Continuation of current trajectory; "political commitment" (medium) | P-2: N/A | 8,000 kg-SWU /yr | 24,000-28,000 kg-SWU /yr |
| | • Nuclear weapons progress is steady and successful (high estimate) | P-2: 4,000-5,000 | 16,000-20,000 kg-SWU /yr | 48,000-58,000 kg-SWU /yr |
| Bistline et al. | • Constraints: procurement of maraging steel; high-strength aluminum; pivot bearings | N/A | Most likely is 35,000 kg-SWU /yr | N/A |
| Braun | • Known capacity is mirrored at covert production-scale plant; | P-2: 8,700 | 34,600 kg-SWU /yr | N/A |
| | • P-2 centrifuge production rate of 2,000 every 2 years | P-2: 8,000 | 26,660 kg-SWU / yr | 34,660 kg-SWU / yr |

the weaponization program by 2015 or later. All of these estimates rely on the few direct observations Hecker was able to make during the 2010 visit and numerous assumptions based on indirect observations. In addition to these uncertainties, we also do not know what portion of the enrichment capacity was dedicated to fuel production for the ELWR and when (if at all) that capacity was modified to produce HEU for the weapons program.

There also exists the possibility that some enrichment capacity was dedicated to the production of enriched fuel for the IRT-2000 reactor to enhance its capability to produce medical isotopes or to be used to irradiate lithium targets for tritium production. Thus, while enrichment capacity estimates are tenuous, plant utilization estimates are even more tenuous. Nevertheless, in Table 4 we provide the best estimates for the end of 2016 based on our understanding of the North

*Table 4. Estimates of Highly Enriched Uranium Stockpile in North Korea by 2015*

| Reference | HEU Stockpile by end of 2016<br>Annual production rates |
|---|---|
| Albright[38] | 133-502 kg (1)<br>24-170 kg/yr by 2020 |
| Hecker (based on Bistline et al.)[39] | 300 to 450 kg (2)<br>150 kg/yr |
| Braun in Braun et al. | ~200 kg (3)<br>100 kg/yr |

(1) We present the low and high estimates derived from Albright's study as extrapolated from the values given for end of 2014 and our 2016 estimates based on Albright's annual rates projected to 2020.
(2) Annual rate of 150 kg/year is based on probabilistic estimate taking into account the availability of key materials such as maraging steel. The 2016 stockpiles are estimated based on an estimated schedule of operations of known and suspected centrifuge plants.
(3) Braun assumed that the North Korean production complex reached annual production capacity of 100-130 kg U-235 in 2015. He further assumed that the enrichment capacity was dedicated mostly to LEU production until the end of 2014 and reverted to HEU production only in 2015. He estimated the HEU stockpile to be about 200 kg by the end of 2016 and increase by at about 100 kg/year minus any amount that may be used for IRT-2000 fuel.

Korean enrichment complex. We also present the estimates of Albright who has conducted detailed analysis of fissile material production in North Korea.

## IV. Possible Tritium Production

North Korea announced in 2010 that it had achieved fusion,[40] which would require the availability of tritium. In addition, North

38. David Albright, "Future Directions in the DPRK's Nuclear Weapons Program: Three Scenarios for 2020," *U.S.-Korea Institute at SAIS* (February 2015), ([http://38north.org/wp-content/uploads/2015/02/NKNF-Future-Directions-2020-Albright-0215.pdf]).
39. Bistline et al. "A Bayesian Model."
40. Justin McCurry, "North Korea Claims Fusion Breakthrough," *The Guardian* (May 12, 2010), ([https://www.theguardian.com/world/2010/may/12/north-korea-creates-nuclear-fusion-claim]).

Korea announced in January 2016 that it tested a hydrogen bomb, which would also require tritium. This raises the issue of how and where tritium could be produced for North Korea's nuclear weapons program, either for boosted fission weapons or thermonuclear weapons.[41]

North Korea would need to master the technologies of Lithium-6 enrichment and of tritium separation from irradiated lithium targets in order to provide the requisite tritium for the weapons program. The United States and the Soviet Union mastered these technologies during the 1950's and so it would not be surprising if North Korea has acquired some degree of proficiency in these technologies during the past five years.

Tritium, along with helium, is produced by neutron irradiation of Li-6 targets, which North Korea could achieve in either the IRT-2000 or the 5MWe reactor. North Korea has operated the IRT-2000 reactor only sporadically for the past 25 years because of the lack of HEU reactor fuel. This mode of operation is not suitable for tritium production, which requires continued irradiation for several months (or years) depending on the amount of tritium required. Thus, should North Korea wish to employ the IRT-2000 reactor for lithium targets irradiation it would have to domestically produce new HEU fuel elements. The IRT-2000 contains several irradiation tubes passing through the center of the reactor where lithium targets could be inserted. This option would produce only limited amounts of tritium considering the small size of the IRT-2000 reactor and the limited capacity of the irradiation tubes.

Irradiation of lithium targets could be done in one of two ways in

41. In a boosted fission device, fusion is produced in a mixture of tritium and deuterium contained inside a hollow fission device. The fusion reaction enhances (or boosts) the fission reaction in the fission fuel. The advantage of boosted devices stems from the fact that they can be more easily miniaturized. In a two-stage thermonuclear weapon a fission device, called the primary, is used to drive, that is create fusion, in a secondary containing tritium and deuterium. If deuterium is needed, North Korea should have no problem producing it by isotope separation techniques.

the 5MWe reactor. Lithium targets could be inserted in standard vertical fuel element channels and removed when the lithium is considered sufficiently irradiated. The other option would be to construct new, dedicated irradiation tubes from outside reaching the center of the reactor's core and placing the lithium targets only in the irradiation tube(s). While the second option is feasible, it will limit the number of lithium targets that could be irradiated at any time. Regardless of the irradiation method chosen, there is also a trade-off inherent in this tritium production method. The neutrons absorbed in the lithium targets are thus not available for plutonium production. During 2014 and 2015 there were several reported shutdowns of the reactor. It is conceivable, although there is no direct evidence, that lithium targets that were irradiated in the reactor were removed at that time. We note that the ELWR could also be used to irradiate targets for tritium production once it becomes operational.

Two potential sites exist in the Yongbyon nuclear center that could be used for processing irradiated lithium targets for tritium extraction. First, the existing hot cells in the isotopes production laboratory located near the IRT-2000 reactor or second, a possible new hot cell facility now under construction at the southeastern part of the fuel fabrication plant. The large RCL is likely not used for tritium extraction since it is dedicated to plutonium extraction from the highly radioactive spent fuel using the PUREX process as explained above.

A new facility has been observed in satellite imagery to be under construction at the southeastern corner of the Fuel Fabrication Facility in the Yongbyon nuclear center.[42] This facility was seen during its construction stages in 2014 to contain what looked like five hot cells

42. William Mugford, "North Korea's Yongbyon Nuclear Facility: Sporadic Operations at the 5 MWe Reactor But Construction Elsewhere Moves Forward," *38 North* (July 24, 2015), ([http://38north.org/2015/07/yongbyon072415/]). Also, David Albright and Serena Kelleher-Vergantini, *Update on North Korea's Yongbyon Nuclear Site* (Washington D.C.: Institute for Science and International Security, September 15, 2015), ([http://isis-online.org/uploads/isis-reports/documents/Update_on_North_Koreas_Yongbyon_Nuclear_Site_September15_2015_Final.pdf]).

arranged in a row, facing a large operating floor. The facility was covered with a roof in 2015 and it has been impossible since to learn more regarding its mission or the progress made in its completion. A tall stack seen near the facility could serve for discharging non-condensable (presumably radioactive) gases from chemical separation operations to the atmosphere. It is difficult to estimate when the interior work will be completed and when will it start operations. The available imagery also does not provide any information on what kind of operations are planned for this facility once it is completed. The hot cells appear to have less concrete shielding than the radiochemical laboratory. They are also smaller and appear more suitable for processing irradiated targets rather than for processing of highly radioactive spent-fuel elements. Therefore, it is quite possible that the new hot cells facility might be used as a modern dedicated tritium production facility. However, any tritium extracted to date was likely done in the isotope production laboratory in the IRT-2000 reactor complex.

## V. From Fissile Materials to Bombs

A functional nuclear arsenal requires not only fissile materials, but also weaponization and a method of delivering the weapons. Weaponization and missile delivery are covered elsewhere in this volume. In this section, we provide a short analysis of how much fissile material may be required for North Korea's nuclear weapons to put the stockpiles we have estimated into context of the threats they pose. Our focus is as much on why North Korea would choose either plutonium or HEU, as on the specific amounts of fissile materials used.

We know very little about North Korea's weaponization effort — that is, the design and manufacture of North Korea's nuclear weapons. Therefore, estimates of how many weapons worth of fissile materials North Korea possesses suffer from this additional uncertainty. We do know that North Korea has tested nuclear devices of significant nuclear explosion yield. Four of the five nuclear tests appear to have been successful. The most recent test in September 2016 produced an apparent explosion yield of 15 to 20 kilotons (in the range of the Nagasaki bomb).[43] We are also quite certain that the 2006 test was based on a plutonium design per discussion between Yongbyon Director Ri Hong-sop and Hecker. We believe that the 2009 and 2013 tests also used plutonium. North Korea likely introduced HEU into its testing program and its nuclear weapon stockpile some time around 2013.

Pyongyang has publically announced that it has successfully miniaturized nuclear devices that it is able to launch on its missiles. Smaller and lighter warheads allow missile delivery at greater range. We therefore assume that North Korea's program is focused primarily on implosion-assembly nuclear devices, rather than larger gun-assembly devices. Plutonium has superior nuclear physics characteristics for miniaturized devices compared to HEU. In fact, it is believed to be the fissile material of choice in the stockpiles of the nuclear weapons states.

With initial test experience based on plutonium, why would North Korea change from plutonium to HEU? Before the Agreed Framework, North Korea was on the path to be able to produce up to 300 kg plutonium annually, far exceeding its nuclear weapon needs. Yet after the demise of the Agreed Framework, it was left with a capacity of at most 6 kg per year. As shown above, it has not been able to produce even that amount consistently. Hence, without building a new plutonium production reactor, the plutonium path was essentially at a dead end. It is possible that the ELWR may have been planned as a backup for plutonium production, but it has taken much longer to construct and operate than it would have taken North Korea to build a new 50 MWe gas-graphite reactor with the capacity for roughly 60 kg plutonium annually. It is also likely that North Korea had all the requisite materials and technology to construct such a reactor since its previous effort was close to completion in 1994.

One possible explanation is that operation of the 5 MWe reactor

43. Hecker, "What to Make of North Korea's Latest Nuclear Test?"

and construction of a new reactor would be highly visible and plutonium production predictable. On the other hand, centrifuge facilities can easily be hidden, thereby greatly increasing the uncertainty of estimating the size of North Korea's weapon program. It appears that North Korea had little concern about a military attack on its nuclear facilities since it decided to construct the Yongbyon centrifuge facility in full view of satellites. However, in spite of putting its enrichment facilities in Yongbyon within full view, Pyongyang was able to introduce a huge level of uncertainty about the size of its weapon program.

Another possibility is that North Korea is believed to have received weapon design information for a HEU-fueled implosion-assembly device from A.Q. Khan, who is reported to have acquired such information from China.[44] If Khan provided North Korea with additional information, such as nuclear test performance and tacit fabrication information, then North Korea may have concluded that HEU offers a more assured path to a miniaturized device than their own indigenous plutonium effort. It is also possible that North Korea may want the ability to produce HEU to use in future two-stage thermonuclear fusion weapons.

Pyongyang has also been interested in building a light water reactor for the past 30 years. Now that they have decided to build it indigenously, they needed to develop uranium enrichment capabilities, albeit to produce LEU rather than HEU. North Korea also has a civilian need for HEU. Since the demise of the Soviet Union, it has not been able to get fresh HEU fuel for its IRT-2000 reactor, which was used for medical isotope production and research. Some of the capacity developed for the weapon program could be used to provide such fuel.

There is significant disagreement in the open literature about the amount of fissile materials required for fission devices. The Nagasaki bomb contained roughly 6 kilograms of plutonium and the Hiroshima

---

44. David Albright and Paul Brannan, *Taking Stock: North Korea's Uranium Enrichment Program* (Washington, D.C.: Institute for Science and International Security, October 2010), ([http://isis-online.org/uploads/isis-reports/documents/ISIS_DPRK_UEP.pdf]).

gun-assembly bomb contained roughly 60 kilograms of HEU. The International Atomic Energy Agency defines a Significant Quantity, the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded, as 8 kg for plutonium and 25 kg for HEU. Considering its nuclear testing history, it is conceivable that North Korea may be able to produce a device with 4 to 6 kg of plutonium or roughly 15 to 25 kg of HEU. For the purpose of estimating how many nuclear devices North Korea could build by the end of 2016, we assume 5 kg and 20 kg for one bomb's worth of plutonium or HEU, respectively.

The estimates of fissile materials stockpiles presented above indicate that North Korea may possess roughly 20 to 40 kg of plutonium and 200 to 450 kg of HEU by the end of 2016. Its annual production capacity for plutonium is less than 6 kg plutonium and may be as high as 150 kg of HEU. On the basis of the earlier discussion of the amount of fissile material required per weapon, North Korea may possess sufficient fissile material for 4 to 8 plutonium weapons and 6 to 20 HEU weapons with an annual production capacity of at most one plutonium weapon and possibly 6 HEU weapons. The estimates by Albright et al. are similar for fissile materials, but they allow for the possibility that North Korea may be more efficient in its use of fissile materials. We don't rule out that possibility, but do not consider it likely. The important factor is that while plutonium production rate is constrained by the characteristics of the 5 MWe reactor, HEU production rate could be increased at will, constrained only by centrifuge components availability. And, perhaps just as importantly, the uncertainty presents enormous political challenges of how to respond to North Korea's program.

## VI. Summary

Estimates of plutonium and HEU inventories and annual production rates have been developed based on an analysis of North Korea's production facilities. The estimated plutonium inventories of

20-40 kg with an annual production rate of less than 6 kg are bounded with good confidence. The confidence in these estimates stems from the fact that international inspectors, U.S. technical teams and one of the authors (Hecker) have had extensive access to the facilities and held detailed discussions with Yongbyon's nuclear specialists. Moreover these sites are readily monitored by satellite imagery.

The estimated HEU inventories of 200-450 kg with an annual production rate of ~150 kg are highly uncertain. These estimates suffer from being based almost exclusively on indirect evidence. The only direct observations of North Korea's uranium centrifuge program were those reported by Hecker after his visit in 2010.[45] This visit confirmed the existence of centrifuge uranium enrichment capability, but did not confirm the production of HEU. In addition, the footprint of centrifuge enrichment facilities is small and easily concealed making observation from the outside problematic. However, the circumstantial evidence of the expansion of the Yongbyon nuclear complex and the fact that North Korea conducted two additional nuclear tests in 2016 indicate that it has developed a substantial capacity for an HEU arsenal. However, the uncertainty itself associated with the HEU capacity has policy implications. We have also shown that North Korea has the capability to produce at least small quantities of tritium, which are required should Pyongyang decide to pursue boosted fission weapons or thermonuclear weapons.

45. Hecker, *North Korea's Yongbyon Nuclear Complex: A Report by Siegfried S. Hecker*.