Institute for Science and International Security (ISIS)

North Korea's Estimated Stocks of Plutonium and Weapon-Grade Uranium

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Executive Summary and Findings[1]

Rationale

For years, great controversy has surrounded North Korea's uranium enrichment program (UEP). How large is it? Has it made weapon-grade uranium (WGU)? How much could it make in the future? But there are also broader questions. What is the role of the UEP in the larger North Korean nuclear program? Is the UEP program strictly oriented to make 3.5 percent low enriched uranium for a civilian light water reactor (LWR) under construction at the Yongbyon nuclear complex, as North Korea says? Is it to make WGU? Or could North Korea intend to further enrich uranium for use in the light water reactor to make plutonium for nuclear weapons? Although LWRs are not typically used to make weapon-grade plutonium, they can do so efficiently if the reactor core is specially designed. Finally, how should the United States respond to the UEP and the associated uncertainties in this program?

This ISIS report attempts to answer these questions utilizing plausible scenarios about past and possible future operation of the centrifuge program that could result in the production of WGU and future operation of the LWR that could make weapon-grade plutonium. In doing so, the report seeks to organize the incomplete data and derive answers to the above questions that have policy relevance.

The report's results are necessarily preliminary because significant uncertainties exist about the number of North Korean gas centrifuge plants, their operation, and the amount and enrichment level of the enriched uranium produced in them. In addition, although North Korea has said that its Yongbyon LWR is for civilian purposes, this statement is unverified and doubts about its potential use are justified. This report is designed to be updated if and when additional information is obtained.

Findings

This report presents and evaluates a wide range of information about North Korea's plutonium and uranium enrichment programs. It identifies gaps in knowledge of these programs.

For this report, ISIS developed a variety of estimates of North Korea's current and future stocks of WGU and weapon-grade plutonium. Although the numerical possibilities are broad, most of the discussion focuses on the central estimates.

[1] Dr. Houston Wood of the University of Virginia and a consultant to ISIS made significant contributions to this report's section on uranium enrichment. In particular, he played an important role in developing the scenarios and predicting enriched uranium outputs.

These results are presented in terms of kilograms of these materials. This report, and in particular this summary, uses the convention of converting these numbers into nuclear weapon equivalents. Often the term "equivalents" is dropped. Such a conversion is necessary when both plutonium and WGU estimates are discussed, since it allows for a more meaningful discussion of the aggregate amount of both fissile materials.

Historical Production of WGU and Weapon-Grade Plutonium. The report develops several scenarios whereby North Korea could have produced WGU in its centrifuge program, considering cases where North Korea has or does not have a second centrifuge plant. Despite North Korea's deployment of gas centrifuges, a credible lower bound on WGU production through 2011 is near zero and not enough for a nuclear weapon. The Yongbyon centrifuge plant could be its first enrichment plant, although it likely also operated a pilot plant elsewhere. If a second enrichment plant exists, which is also credible, North Korea could have made a substantial amount of WGU. An upper bound estimate is that North Korea has enough WGU for a dozen or more nuclear weapon equivalents, where each weapon is assumed to contain 20 kilograms of WGU. Based on considering all the scenarios, the central estimates are that North Korea has as of the end of 2011 enough WGU for 0 to 11 nuclear weapons. The upper bound central estimates cluster in the range of 4-7 nuclear weapons. As can be seen, this estimate is fraught with uncertainty, which explains why the results are necessarily preliminary.

Currently, North Korea's plutonium inventory appears capped, with enough for 6-18 nuclear weapons and a midpoint of 12 nuclear weapons. It could add marginally to this number if it restarted its 5 megawatt-electric (MWe) reactor at Yongbyon.

Thus, considering central estimates only, as of the end of 2011 North Korea has enough fissile material for 12-23 nuclear weapons. The lower bound of the WGU estimate is zero weapons-worth, or a total central estimate of 12 weapons worth of fissile material. The upper bounds of the central WGU estimates cluster in the range of 4-7 weapons, resulting in a total of 16-19 nuclear weapons.

Projected Production of WGU and Weapon-Grade Plutonium. North Korea is not thought to be currently making weapon-grade plutonium. It remains unconfirmed if North Korea is making WGU today. However, it could be doing so, even if it possesses only the Yongbyon centrifuge plant. By the time period 2015-2016, it could produce a significant amount of WGU. It could also resume weapon-grade plutonium production in that time frame.

Developing estimates of future production of fissile material is complicated because North Korea's rationale for building a gas centrifuge plant is not well understood. The UEP's purpose may be more involved than only producing 3.5 percent LEU for a civilian LWR or for that matter just making WGU for fission weapons similar to its plutonium-based weapons. In fact, the development of gas centrifuges provides North Korea with flexibility in building more sophisticated nuclear weapons.

The enriched uranium output of the UEP could also be used to make weapon-grade plutonium in the LWR. The LWR's core could be designed to optimize the production of weapon-grade plutonium for nuclear weapons through the use of a driver fuel, which could be enriched to 10-20 percent, and targets of natural or depleted uranium in which weapon-grade plutonium would be produced. Combined with the construction of a LWR, the centrifuge program thus provides North Korea with the capability to greatly expand its nuclear arsenal and build more advanced nuclear weapons. This case requires North Korea to take a significant technological risk using interlocking LWR and centrifuge programs. But it offers several advantages. This approach would allow North Korea to utilize its existing family of plutonium-based nuclear weapons designs. Its rate of production of weapon-grade plutonium could far exceed the rate of plutonium production in the 5 MWe reactor at Yongbyon.

This report evaluates three cases of future production of WGU and weapon-grade plutonium and projecting central estimates of the number of nuclear weapons that North Korea could produce over the next five years, until the end of 2016. In this period, the number of centrifuges operational is projected to also increase, at a rate of 1,000 P2 centrifuges a year starting in 2014 at each centrifuge plant considered in specific scenarios. As expected, all of these projections, which are shown in table 5 in the report, show an increase in North Korea's nuclear weapons arsenal.

The three cases are:

1) North Korea does not make any more plutonium for weapons, but it produces LEU for the experimental LWR. In the scenario where the Yongbyon centrifuge plant is the only one, North Korea is projected to have 14-25 nuclear weapons by the end of 2016, a change of two nuclear weapons from its arsenal as of the start of 2012. In this scenario, almost all the centrifuge output goes to make LEU for the LWR. In the scenario where there is a second enrichment plant, there is a modest growth in the number of nuclear weapons to 23-34 nuclear weapons, which represents an average growth of about two nuclear weapons per year during this five-year period.

If the experimental LWR is not intended to make plutonium for nuclear weapons, as North Korea has stated, the reactor's requirement for LEU would significantly reduce North Korea's ability to use its enrichment program to make WGU for nuclear weapons. In this case, the growth in North Korea's arsenal is projected to be relatively small over the next five years.

2) North Korea optimizes the LWR for making weapon-grade plutonium. Under the scenario of one centrifuge plant, North Korea would likely have enough enrichment capacity to produce a limited amount of weapon-grade uranium for advanced nuclear weapons. By the end of 2016, North Korea is projected to have 28-39 nuclear weapons, or an increase of 16 weapons since the end of 2011; all but one would be produced in 2015 and 2016. If North Korea has two centrifuge plants, however, it could produce a much larger quantity of WGU. It could have 37-48 nuclear weapons, or an increase of 25 weapons, most of which would be produced in 2015 and 2016. As shown, the LWR

would be an efficient way to significantly increase the number of North Korea's nuclear weapons using plutonium while leaving enough enrichment capacity to make weapon-grade uranium for more advanced nuclear weapons. However, the cost to North Korea is that weapons production would be delayed by several years as the LWR comes into operation.

3) North Korea does not provide LEU to the LWR, but instead dedicates centrifuge capacity to making WGU. Since North Korea has expressed its intention to operate the LWR, this case is for comparison purposes. In the scenario of one centrifuge plant, North Korea could accumulate enough WGU for 21-32 nuclear weapons by the end of 2016. With two centrifuge plants, it could have 26-37 nuclear weapons by the end of 2016. These projections show that if the LWR is dedicated to making weapon-grade plutonium for weapons, in the longer term North Korea could produce more nuclear weapons using this route than if it dedicated all its centrifuge capacity to making WGU. However, this result must be tempered by the fact that the difference would be less if instead of 20 kilograms of WGU per weapon, only 15 kilograms of WGU were needed per weapon, something which may be possible for North Korea to do. Thus, given such uncertainties the relative differences between cases 2 and 3 should not be overly emphasized.

But in any event, cases 2 and 3 show that dedicating a significant portion of the centrifuge capacity to producing LEU for the LWR to make weapon-grade plutonium does not necessarily reduce the total number of projected North Korean nuclear weapons, compared to allocating all the centrifuge capacity to making WGU and not making any LEU for the LWR. Under certain circumstances, if the LWR is dedicated to making weapon-grade plutonium, North Korea could produce more nuclear weapons than if it dedicated its centrifuge capacity to making WGU only. However, this strategy does delay the attainment of those weapons and assumes that both the centrifuge program and the LWR succeed.

Recommendations

The estimates of stocks of WGU and projected stocks of WGU and weapon-grade plutonium appear dominated by uncertainties. With such large uncertainties, a central challenge is learning more about North Korea's nuclear program and its intentions. A priority is thus determining whether there is a secret centrifuge plant in addition to the Yongbyon centrifuge plant, how many P2-type centrifuges in total have been deployed successfully, and how well have these centrifuges operated. In addition, can North Korea produce enough LEU for the LWR? What is the design of the LWR core, and will it make plutonium for nuclear weapons?

Regardless of the accuracy of the estimates, it is critical to take steps that reduce the chances that North Korea will increase the size of its nuclear arsenal. In essence, the United States and its allies should develop measures today to head off this future potential threat. This strategy should include both an attempt to negotiate a solution and increase efforts to detect, thwart, and delay North Korea's nuclear progress.

The approach of achieving pre-steps as a precondition for the resumption of the Six Party Talks remains a useful way to cap North Korea's uranium enrichment program and head off the use of the LWR to make weapon-grade plutonium. As such, negotiations should attempt to re-establish this approach. Future pre-steps should include a North Korean commitment not to use any domestically produced LEU in the LWR in addition to a verified moratorium on operations at the Yongbyon centrifuge plant. North Korea should also commit not to use the LWR to make plutonium for nuclear weapons and not to reprocess any of the LWR's irradiated fuel. A complete set of recommendations on possible future negotiations is outlined in the main report.

If negotiations resume, the issue of the experimental LWR should be taken up. As an incentive, the international community could offer North Korea 3-4 percent LEU fuel for this LWR, subject to the conditions that it would never use domestically produced LEU and the supplied LEU, after irradiation and cooling, would be returned to the supplier.

Looking again into the future, North Korea's centrifuge program poses several complicated challenges to establishing a uranium enrichment program disablement and verification regime, in particular (1) gaining assurance in the completeness of a North Korean list of centrifuge facilities subject to disablement, and (2) verifying a declaration of the total amount and type of enriched uranium produced in the enrichment program. The United States should start now to carefully prepare for these verification and negotiation challenges.

Absent successful diplomatic efforts, the United States should use its experience with Iran's nuclear program to develop strategies to better understand and delay North Korea's nuclear weapons efforts. These efforts should aim to better characterize North Korea's secret centrifuge facilities and activities and develop methods to thwart or delay progress in the centrifuge program.

Like Iran, North Korea remains dependent on foreign supply for its centrifuge program and its procurements for this program are on going. Delaying progress in North Korea's program hinges on interrupting its successful smuggling networks, many of which have successfully infiltrated Chinese markets to acquire a range of dual-use items necessary for its centrifuge program from both Chinese private companies and high-tech foreign suppliers.

Although China has taken measures to bolster its laws and practices, it simply does not do enough to stop smuggling operations put forth by North Korea. *China needs to strengthen its export control laws and improve their enforcement. It also needs to support the improvement of U.N. Security Council sanctions that aim to ensure that North Korea cannot acquire goods for its nuclear programs.* The United States should continue to address this issue at the highest levels of U.S./Chinese diplomatic and military interaction.

In collaboration with China and other members of the Security Council, the United States should develop a new U.N. Security Council resolution that clarifies and greatly expands the list of goods banned for sale to North Korea's nuclear and missile programs. The new resolution in particular should make it harder for North Korea to succeed in buying what it needs to maintain and expand its centrifuge program.

Although public discussions generally complicate negotiations with China, they can serve to highlight actions that are damaging or counterproductive, giving China additional incentive to address these problems. Keeping all the interactions secret can also shield China against accountability. Thus, the U.S. government should selectively make certain cases and problems public and make clear the desired remedy.

The United States should seek additional cooperation from U.S. industries with subsidiaries in China to detect and thwart DPRK smuggling efforts. It should model this effort on those already being done in Britain and Germany.

The proliferation of gas centrifuge technology, nuclear materials, and dual-use goods, such as maraging steel, remains a central concern. Despite widespread suspicion about its continued actions, North Korea has agreed on multiple occasions not to proliferate nuclear materials, technology, or know-how. *A goal should be to strengthen North Korea's non-proliferation commitment and seek a public reaffirmation of these commitments. This strengthening should include a verifiable North Korean pledge not to illicitly procure for its own nuclear programs or for the programs of other countries or groups.* Absent North Korea's adherence to these commitments, North Korea should be subject to additional U.N. Security resolutions and domestic sanctions legislation that seek to make North Korean proliferation and smuggling more detectable and harder to accomplish.

Final Word

As in many other cases, negotiations are the best way to alleviate the security challenges posed by North Korea's growing nuclear program. They should be pursued vigorously. Absent negotiations, however, the United States has few options than increasing its efforts to make it more difficult for North Korea to make progress on its nuclear weapons programs.

Introduction

On February 29, 2012, North Korea announced that it would halt nuclear tests and long-range missile launches, and place a moratorium on enrichment activities that would be monitored by the International Atomic Energy Agency (IAEA). These pledges represented necessary pre-steps by North Korea towards the resumption of the Six Party Talks. However, North Korea tested a space launch in mid-April, which the international community viewed as a violation of its pledge. Although the missile failed soon after lift-off, the damage to restarting negotiations was inevitable. Widespread international condemnation followed the launch, and North Korea announced it would not implement its enrichment moratorium. Now, the question is whether it will seek to make weapon-grade uranium for nuclear weapons. Moreover, North Korea has discussed whether to overtly deploy nuclear warheads on its missiles. With such great uncertainty about North Korea's nuclear plans, it is important to take stock of both its uranium enrichment and plutonium programs. In particular, this report examines North Korea's existing and possible stocks of separated plutonium and weapon-grade uranium and their potential growth during the next several years. It also makes a series of recommendations to reduce the threat posed by these stocks.

Background

North Korea embarked on a nuclear weapons program in the early 1980s when it started building a small nuclear reactor at the Yongbyon nuclear site north of Pyongyang. To make nuclear weapons, North Korea until recently has concentrated on increasing its stocks of separated weapon-grade plutonium.

During the late 1980s and early 1990s North Korea built a clandestine plutonium separation plant at Yongbyon, and during this time, it may have secretly produced and separated enough plutonium for one or two nuclear weapons, despite signing the Nuclear Non-Proliferation Treaty (NPT) in 1985.

In 1992, North Korea finally submitted its safeguards declaration to the IAEA, which is required under the NPT. However, the IAEA challenged the completeness of North Korea's plutonium declaration, assessing that North Korea had produced more plutonium than it had declared.[2] That discrepancy remains between the IAEA's investigation and North Korea's official declaration of the amount of plutonium separated at Yongbyon. Despite this difference, North Korea froze its plutonium program at Yongbyon in 1994 in an agreement reached with the United States.

In October 2002, Bush Administration officials in Pyongyang accused North Korea of having a secret, relatively large uranium enrichment program that could make weapon-

[2] See Albright and Kevin O'Neill, *Solving the North Korean Nuclear Puzzle* (Washington, D.C.: ISIS Press, 2000).

grade uranium (WGU) for nuclear weapons. However, no confidence was established about the size of this program at the time.[3]

After U.S. charges of a secret uranium enrichment program, tensions escalated on the Korean peninsula, leading North Korea to deny it had any such program and suspend its plutonium-freeze at the Yongbyon site in late 2002. It proceeded to restart its 5 megawatt-electric (MWe) reactor and plutonium separation plant at the site. It then declared it was making nuclear weapons.

Eventually, after the success of the Six Party Talks in the mid-2000s, North Korea shut down both the small reactor and reprocessing plant. However, by 2009, these talks collapsed. Nonetheless, North Korea has not restarted the small reactor, but it operated the separation plant briefly to process a stock of irradiated fuel from the 5 MWe reactor, obtaining a small addition to its total separated plutonium stock.

North Korea's interest in gas centrifuges dates to the late 1980s, although progress in this area has been slow and dependent on foreign assistance. After over two decades of development and many denials, in November 2010, North Korea revealed a production-scale gas centrifuge plant at the Yongbyon site, while denying the existence of any other production-scale plant. In late 2011, North Korea stated it was making only low-enriched uranium (LEU).

North Korea's plutonium production capabilities are well known especially compared to those of its uranium enrichment program. There remains no definitive answer to how much enriched uranium North Korea has produced and how much weapon-grade uranium it has accumulated.

Plutonium Capabilities

The Yongbyon nuclear site is the center of North Korea's plutonium production capability. After North Korea agreed to disable its plutonium program during the Six Party Talks in 2007, it started withdrawing the fuel from the Yongbyon reactor's core and took a number of other disablement steps at the reactor, plutonium separation plant, and fuel fabrication plant. In a dramatic move, it destroyed the reactor's cooling tower in June 2008, allowing outside media to record its destruction.

Following the collapse of the disablement process in 2009, North Korea stated that it had restarted the plutonium separation plant at Yongbyon and processed all the irradiated fuel in the last reactor core, extracting the plutonium. Commercial satellite imagery has shown that North Korea has not rebuilt the cooling tower, implying that it has not restarted this reactor. However, North Korea started building a light water reactor next to the old cooling tower.

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[3] David Albright and Paul Brannan, *Taking Stock: North Korea's Uranium Enrichment Program*, Institute for Science and International Security, October 8, 2010.

During the Six Party disablement process in 2008, North Korea declared that it had about 30 kilograms of separated plutonium. This net value reflected plutonium consumed by the 2006 underground test and the inevitable loss of some plutonium in the operation of the plutonium separation plant. It declared the latter as two kilograms of plutonium.[4] Surprisingly, it also said that the 2006 underground nuclear test used only two kilograms of plutonium, far less than the standard 4-6 kilograms often believed to be in each North Korean nuclear weapon. Two kilograms of plutonium would imply a fairly sophisticated nuclear weapon design that North Korea was not believed to have mastered. Perhaps, this is why North Korea announced that the expected explosive yields of its 2006 and 2009 tests were significantly lower than expected. In this case, the lower yield of about four kilotons would have resulted from the miniaturization of the devices, where yield had been sacrificed for device size. In addition, the failure of the 2006 test may have resulted from seeking to test an advanced design. Alternatively, this claim of two kilograms of plutonium may be a bluff, part of a North Korean strategy to create ambiguity about its nuclear capabilities and thus increase hesitation on the part of its enemies, particularly the United States.

The last reactor core reportedly contained about eight kilograms of plutonium, increasing North Korea's declared total to 38 kilograms prior to the 2009 test. Subtracting 2-4 kilograms likely used in the 2009 test, North Korea is estimated to have a stock of 34-36 kilograms of plutonium for nuclear weapons.

North Korea's plutonium declaration falls at or below the lower end of the range predicted by estimating the operation of the Yongbyon reactor and subsequent separation of plutonium. For example, Siegfried S. Hecker, former Director of Los Alamos National Laboratory and a frequent visitor to North Korea, estimated in 2006 that North Korea produced an inventory of between 40 and 50 kilograms of plutonium before its 2006 nuclear test.[5] ISIS assessed in 2007 that North Korea had between 28 and 50 kilograms of separated plutonium following the 2006 test but before the last core was discharged and the 2009 test.[6]

Verification of North Korea's plutonium declaration had just started prior to the end of the Six Party process in 2009 and debate continues over whether North Korea declared all its plutonium. There are two periods of time where questions remain. As mentioned above, the IAEA uncovered evidence that in the early 1990s, North Korea did not declare kilogram quantities of separated plutonium, estimated by the United States at the time as about 8-9 kilograms of plutonium but no more than ten kilograms.[7] In addition, with regard to the operation of the reactor from 2003-2008, North Korea could have under-

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[4] In a plutonium separation plant like the one at Yongbyon, some plutonium ends up in the nuclear waste or held-up in pipes and equipment. In this case, the plutonium losses comprise roughly five percent of the total plutonium declared as separated. These losses still require independent verification of their size and nature.

[5] Siegfried S. Hecker and William Liou, "Dangerous Dealings: North Korea's Nuclear Capabilities and the Threat of Export to Iran," *Arms Control Today*, vol. 37, no. 2, pp. 6–11.

[6] Albright and Brannan, *The North Korean Plutonium Stock*, ISIS, February 20, 2007.

[7] *The North Korean Plutonium Stock*, op. cit. and , *Solving the North Korean Nuclear Puzzle*, op. cit.

declared its plutonium production in the reactor. Another anomaly is North Korea's statement that it used only two kilograms in its 2006 test.

North Korea denied that it has produced or separated more plutonium than it has declared. To help the United States verify its declaration, North Korea turned over 15,000 pages of operating records of the Yongbyon reactor, and the subsequent analysis of these documents reportedly uncovered no evidence of additional plutonium production. Although the reactor documents were an important first step in terms of verifying North Korea's declaration, other measures are also needed, including access to North Korean facilities, sampling, and interviews with personnel involved in these programs. One key step is to analyze the reactor core to determine total plutonium production. The United States says it acquired North Korea's agreement in October 2008 to sample the graphite in the core of the Yongbyon reactor, a method that can provide an estimate of total plutonium production in the reactor. However, North Korea later claimed it never agreed to any sampling of the reactor core, although this was disputed by other parties to the Six Party Talks. Any future verification arrangement will need to include sampling in order to be effective.

Little is known about North Korea's ability to make a deliverable nuclear weapon, although it is likely able to build a warhead, perhaps one of mixed reliability, which can fit atop a Nodong missile with a range of less than 800 miles.[8] Its declaration of two kilograms in its 2006 test would imply that it knows far more about making nuclear weapons than commonly believed, assuming that the statement is not a bluff. Moreover, North Korea has worked on nuclear weaponization for over 20 years, supporting assessments that it can build a warhead for a Nodong missile.

Accepting North Korea's statements about the size of its stock of separated plutonium, or currently 34-36 kilograms, it is possible to estimate the number of nuclear weapons it could build. Assuming that each weapon contains about 2-5 kilograms of plutonium, North Korea could build anywhere from 6 to 18 nuclear weapons. This broad range reflects uncertainties in the amount of plutonium North Korea needs in each weapon. The midpoint is 12 nuclear weapons, where the warheads contain on average about three kilograms of plutonium.

Future Plutonium Production

Despite the collapse of February 2012 U.S./Democratic People's Republic of Korea (DPRK) mutual commitments, the differences in each of their statements on February 29 raise questions about North Korea's plans with regard to plutonium production for weapons. The U.S. statement makes clear that it understood that North Korea would implement a moratorium with monitoring on all nuclear activities at the Yongbyon nuclear center, including uranium enrichment activities.[9] The parallel North Korean

[8] National Air and Space Intelligence Center, *Ballistic and Cruise Missile Threat*, Wright-Patterson Air Force Base, NASIC-1031-0985-09, April 2009.

[9] "To improve the atmosphere for dialogue and demonstrate its commitment to denuclearization, the DPRK has agreed to implement a moratorium on long-range missile launches, nuclear tests and nuclear activities

statement mentions a halt to uranium enrichment activities at Yongbyon but makes no comment about plutonium-related activities, including any monitoring of a moratorium on them.[10] Interpreting North Korean intentions in such a statement is always difficult but the absence of constraints on plutonium production is noticeable and increases suspicions about North Korean intentions in this area.

North Korea is capable of restarting its 5 MWe reactor at Yongbyon. North Korea says it can restart the reactor in three months, since the reactor's operating personnel remain ready and it has enough fuel for a new core. In this case, its future production would be expected to be consistent with past production, namely a fairly slow increase in its plutonium inventory.

North Korea is now building next to the 5 MWe reactor what it calls an experimental light water reactor (LWR). North Korea stated the reactor would produce 100 megawatts-thermal (MWth), or an estimated 30 megawatts of electricity (MWe).[11] Although North Korea first announced that the reactor would be finished in 2012, it is unable to finish it in 2012. ISIS assesses based on satellite imagery analysis that the reactor could be finished in the second half of 2013.[12]

According to Hecker, during his visit in 2010, North Koreans said that the reactor will use uranium dioxide fuel enriched to 3.5% and a full core will contain four tonnes of uranium. In late 2011, North Korea was in the process of working on making LWR fuel. It is unknown if any fuel has been made or which facility makes the fuel. Thus, if the February 29 commitments had been implemented, North Korea would have stopped enriching uranium for this reactor, assuming that a secret centrifuge site either does not exist or would not make such fuel (see section below).

In addition to electricity, this reactor will produce plutonium as a byproduct of its operation. In normal operation, this reactor will produce reactor-grade plutonium, which, while not ideal, could be used directly in nuclear weapons. The use of reactor-grade plutonium in nuclear weapons would result in a lower explosive yield if it were substituted for weapon-grade plutonium in an existing warhead design. Over an extended period of storage, the warhead could also suffer from the extra heat generated by reactor grade plutonium relative to weapon-grade plutonium.

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at Yongbyon, including uranium enrichment activities. The DPRK has also agreed to the return of IAEA inspectors to verify and monitor the moratorium on uranium enrichment activities at Yongbyon and confirm the disablement of the 5-MW reactor and associated facilities." *U.S.-DPRK Bilateral Discussions,* Press Statement, Victoria Nuland, Department Spokesperson, Office of the Spokesperson, Washington, DC, February 29, 2012. http://www.state.gov/r/pa/prs/ps/2012/02/184869.htm

[10] DPRK Foreign Ministry Spokesman on Result of DPRK-U.S. Talks, KCNA, February 29, 2012. http://www.kcna.co.jp/index-e.htm. The North Korean statement mentions only the IAEA monitoring the moratorium on uranium enrichment.

[11] Siegfried S. Hecker, *A Return Trip to North Korea's Yongbyon Nuclear Complex*, Center for International Security and Cooperation, Stanford University, November 20, 2010. http://iis-db.stanford.edu/pubs/23035/HeckerYongbyon.pdf.

[12] Albright and Avagyan, *Update on North Korean Light Water Reactor Construction Project*, ISIS, forthcoming.

Alternatively, the LWR could be operated in a variety of ways to produce weapon-grade plutonium. North Korea could use 3-4 percent enriched uranium fuel and under-irradiate the fuel, withdrawing all or a portion of it when it contains on average weapon-grade plutonium. North Korea would need to modify its reprocessing plant to handle this type of fuel, which in general is more difficult to process than uranium metallic fuel from gas-graphite reactors. Absent recycling of the enriched uranium, this method is very wasteful of the enriched uranium (and enrichment plant capacity). However, it can serve as a way to obtain significant quantities of weapon-grade plutonium if such a need is perceived as urgent.

Another method to harvest weapon-grade plutonium on a more regular basis while utilizing the enriched uranium more efficiently is to cut off and segregate the top and bottom portions of the irradiated fuel elements from the middle section, which is typically far more irradiated. The operations of cutting and segregating would occur in the initial stage of the reprocessing plant, and the segregated sections would be processed and the weapon-grade plutonium extracted, while the middle sections could be processed as waste. However, the fuel would likely still be under irradiated, and the recoverable amounts of weapon-grade plutonium would likely be less than optimal. Nonetheless, if North Korea wanted to increase its stock of weapon-grade plutonium, this method would provide a way to do so.

If North Korea wanted to maximize its output of weapon-grade plutonium while maximizing its use of the enriched uranium in the fuel, it could design a different type of core, namely one using driver fuel and target elements. In this system, the reactor core is composed of both low-enriched uranium driver fuel and depleted or natural uranium targets. The neutrons to create the plutonium would come from the fissioning of uranium 235 in the driver fuel, which could be enriched to 10-20 percent in the isotope uranium 235 and would remain classified as LEU. These neutrons would irradiate the uranium 238 in the targets, producing plutonium. The targets would be replaced in the core when they contained an optimal amount of weapon-grade plutonium. The driver fuel would remain in the reactor until fully irradiated. The U.S. Energy Department studied the use of such a core to make weapon-grade plutonium and tritium in a commercial LWR in the late 1980s. The plan was to use a commercial light water reactor that would have driver fuel enriched to 10 percent and two basic types of targets that would produce either weapon-grade plutonium or tritium.[13]

The driver fuel and targets should be within North Korea's ability to design and make, since it would be similar to fuel containing 3.5 percent LEU. However, the driver fuel would experience significantly higher irradiation levels, possibly posing a challenge to make successfully and leading to greater requirements for enriched uranium if the driver fuel is discharged prior to reaching full irradiation.

The existing plutonium separation plant at Yongbyon would likely need modification to extract the plutonium from the targets. But the targets should be far easier to chemically

[13] Due to a lack of need for weapons plutonium, these plans were never implemented. The United States produces tritium in a commercial light water reactor but the core uses standard LEU.

process than LEU driver fuel or 3.5 percent LEU fuel, which could be stored long-term after irradiation.

If North Korea decided to use the LWR as a source of weapon-grade plutonium for weapons, it could grow its nuclear weapons arsenal significantly by using a driver fuel/target system. Slated to be 100 MWth, or four to five times larger than the existing Yongbyon reactor, the LWR could produce roughly 20 kilograms of weapon-grade plutonium per year. At 2-5 kilograms of plutonium per weapon, twenty kilograms is enough for 4-10 nuclear weapons per year.[14] The actual annual amount of weapon-grade plutonium could vary significantly, depending on the reactor's actual power and performance.

Based on existing evidence of the construction progress of this reactor, such a level of plutonium production would not be expected until about 2015. Such a timeframe would allow for any necessary modifications in the Yongbyon plutonium separation plant.

Uranium Enrichment Program

Much less is known about the status of North Korea's uranium enrichment program. It is known that North Korea acquired up to two dozen centrifuges and a significant amount of technology, materials, and equipment from the Pakistani A.Q. Khan and his colleagues at the Khan Research Laboratories.[15] After years of denial about the existence of such a program, on June 13, 2009, North Korea announced it would commence uranium enrichment, stating, "Enough success has been made in developing uranium enrichment technology to provide nuclear fuel to allow the experimental procedure."[16] Looking back, this announcement appears to represent North Korea's public declaration of its decision to build the Yongbyon enrichment plant, which it revealed in November 2010 to a group of visiting Americans. However, the history and status of North Korea's enrichment activities remain unknown. In particular, how much enriched uranium has North Korea produced, and is any of it highly-enriched uranium?

North Korea is not self-sufficient in the wherewithal to produce gas centrifuges. As a result, it has acquired a wide variety of goods overseas to both develop and build

[14] ISIS did not perform detailed calculations but a rough estimate was conducted with the support of a reactor expert who was familiar with the use of driver fuel/target systems in reactors. The estimate assumes a 70-80 percent capacity factor, a conversion of 0.85 grams of weapon-grade plutonium per megawatt-thermal-days, and an estimated 10 percent reduction in plutonium output to account for the plutonium produced in the driver fuel, which is not usable. The resulting estimate is 19.5-22.3 kg weapon-grade plutonium per year. To assess enrichment requirements, the nuclear reactor expert said that a rule of thumb is that a core composed of 10-20 percent LEU driver fuel would have the same amount of uranium 235 as a core of 3.5 percent LEU fuel.

[15] *Taking Stock: North Korea's Uranium Enrichment Program,* op. cit; and Albright, *Peddling Peril* (New York: Free Press, 2010).

[16] "DPRK Foreign Ministry Declares Strong Counter-Measures against UNSC Resolution," KCNA, June 13, 2009.

centrifuges.[17] These procurements have shed additional light on North Korea's gas centrifuge program.

According to a European intelligence agency, North Korea has sought over the last ten years to procure enough goods to be able to build 10,000 centrifuges. This process appears to be on-going based on North Korean procurements in China which is North Korea's main smuggling platform. North Korea has had an easier time than Iran acquiring needed goods in the last ten years for its centrifuge program. Like Iran, North Korea has successfully developed an illicit purchasing network in China. However, North Koreans are more entrenched in the Chinese economy and share a border with China. As a result, it has more successfully exploited China's weak implementation of export controls and U.N. Security Council sanctions to acquire a wide range of dual-use goods for its centrifuge program.

North Korea, like Iran, hires private Chinese companies to acquire a range of high-tech, dual-use goods and raw materials, including from European and likely U.S. companies based on assessments of individual North Korean procurements. The quality of indigenously produced Chinese high-tech goods remains relatively poor, and centrifuge programs usually need reliable, high quality goods. Thus, these private Chinese companies may approach a supplier in another country or one of the supplier's subsidiaries in China. These companies often violate Chinese export controls or Security Council sanctions either inadvertently or deliberately by then supplying the goods to North Korea. In doing so, these companies may provide false end-user statements to the supplier, typically listing China as the final destination or a company in a nearby country that is viewed as a legitimate end-user. Foreign companies in China have great difficulty spotting these smuggling efforts, and the Chinese government does a poor job exposing these transactions or helping companies to avoid them.

Recently, according to European intelligence officials, North Korea has bought raw materials in China that suggest it is making ring magnets for centrifuge bearings and maraging steel, an important material in centrifuge rotors and bellows. Ring magnets are challenging to produce of sufficient quality for use in centrifuges but generally viewed as within North Korea's growing centrifuge manufacturing capabilities. However, adequate maraging steel is very difficult to make and has been a bottleneck in centrifuge programs in developing countries. These procurements raise the question of whether North Korea can already make maraging steel for centrifuges or is learning to do so. A related concern is whether North Korea has exported or intends to export maraging steel to Iran, which has struggled to acquire enough for its centrifuges and does not appear to be able to make its own.

Yongbyon Centrifuge Facility. On November 12, 2010, North Korea revealed to Stanford University Professor Hecker and his colleagues a 2,000-centrifuge uranium enrichment plant at the Yongbyon nuclear site.[18] The building is located on the site of the fuel fabrication complex at Yongbyon. According to North Korea, it had just started

[17] *Taking Stock: North Korea's Uranium Enrichment Program*, op. cit.
[18] Hecker, *A Return Trip to North Korea's Yongbyon Nuclear Complex*, op. cit.

producing low enriched uranium. However, Hecker obtained no evidence that the centrifuges were operational or had enriched uranium.[19]

Since that time, North Korea is believed to have produced up to 3.5 percent LEU at the plant, but the plant experienced start-up problems. North Korea has stated that this is the first time North Korea has operated such a plant, and this facility was constructed quickly, resulting in problems.

North Korea appears to have had more success than Iran in developing more capable centrifuges. Based on dimensional analysis of Hecker's estimates, the centrifuge appears to be a version of the P2 centrifuge, which is more advanced than the P1 machine that Iran copied and installed in large numbers at the Natanz Fuel Enrichment Plant.[20] Iran is now trying to develop more advanced centrifuges based on the P2 centrifuge.

The centrifuge building, which is approximately 120 meters long and has a blue roof, can be seen in a November 4, 2010 DigitalGlobe satellite image in figure 1 below. When U.S. experts left Yongbyon in April 2009, the building was not involved in centrifuge operations. Figure 2 shows the same building in February 2007. Figure 3 shows the location of the plant relative to the entire Yongbyon site.

Figure 1: Satellite imagery of the North Korean uranium enrichment plant (November 4, 2010).

[19] For example, he did not report hearing the frequency hum of the drive converters. However, he reported that the tops of the centrifuges were in place and the piping attached, which implies that the centrifuges could be operating.

[20] To evaluate Hecker's dimensional estimates, ISIS contacted a centrifuge expert familiar with the P1 and P2 centrifuges. This expert replied, "Hecker's estimate of diameter and length refers to the outside dimensions of the vacuum housing and not to the actual centrifuge rotor. The outside diameter of the P1 and P2 housings differs by only about 15 mm (both being slightly more than 200 mm) and so I doubt whether he could see that difference by eye. The length of the P2 rotor between end caps was 1,050 mm. To this, one has to add the dimensions of the top and bottom bearings, the axial drive motor thickness and the thicknesses of the top and bottom housing flanges. From memory, this amounts to another 400 or 500 mm. The 1,800 mm thus sounds a little long. However, if the vacuum housing is mounted on a pedestal (as seen on some designs and certainly as used in Iran) the overall height from the floor level to the top of the vacuum housing could well be 1,800 mm."

Figure 2: A view of the same building, then the fuel fabrication facility, that was later repurposed to make centrifuges (February 18, 2007).

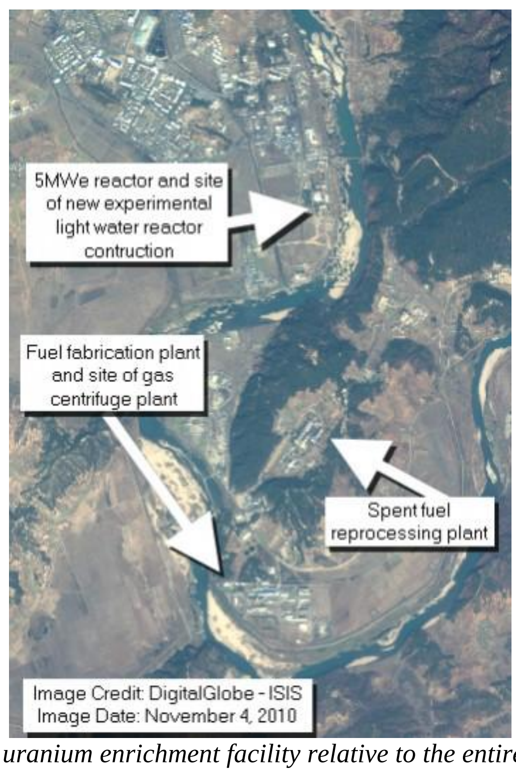

Figure 3: The location of the uranium enrichment facility relative to the entire Yongbyon site (November 3, 2010).

North Korea has stated that the plant's total enrichment capacity is 8,000 separative work units (swu) per year. With 2,000 centrifuges, the average would be four swu per year per centrifuge.

This average value for the North Korean centrifuge is credible, despite being somewhat lower than the output of the original G2 centrifuge, which is the German design stolen by A.Q. Khan in the Netherlands in the 1970s and renamed the P2 (Pakistan-2) centrifuge. (North Korean engineers focused on this machine while present at A.Q. Khan Laboratories in the 1990s.)[21] Each G-2 centrifuge had a capacity of about five swu per year per centrifuge when operated by URENCO in the 1970s. However, documentation from A.Q. Khan passed to Libya specifically mentions that the P2 machine output, when in a cascade, would more likely achieve four swu per year per machine. Actual values could be lower (see below).

Khan's rationale for this statement is not known. This average of four swu per year may reflect a lower enrichment output for each centrifuge than the ones operated at URENCO, or inefficiencies when centrifuges are connected into cascades. In the former case, the lower enrichment output could result from the centrifuge rotor spinning more slowly than originally designed, perhaps due to inferior substitute materials in the centrifuge's construction. However, the North Koreans have not provided their centrifuge's operational speed. Alternatively, assessing the average enrichment output of the North Korean centrifuges across a cascade can incorporate several inefficiencies that reduce total separative output. This loss in efficiency could also be caused by poorly assembled machines that failed to start-up, survive uranium hexafluoride commissioning, or reach operational speed. An advanced industrial state operating the G2 machine could expect these losses to amount to no more than a few percent. Losses in cascade output of North Korean centrifuges, however, may be 20 percent or higher. In this report, the average value of four swu per year per centrifuge when in cascade is taken as the maximum value for the P2 centrifuge model.

Hecker also reported that there were six cascades for an average of 333 centrifuges per cascade, assuming 2,000 centrifuges. This number is almost exactly double the number of P2 centrifuges in the cascades producing LEU in a Pakistani design provided to Libya and Iran by the A.Q. Khan network. However, Pakistan also appears to have had a centrifuge cascade design dedicated to making LEU that had more centrifuges than the cascade design of 164 centrifuges used by Libya and Iran. ISIS has learned of official documentation destined for Libya and found in January 2005 that Pakistan arranged the G2 machine in cascades of 344 centrifuges.[22] According to Khan's 2004 statement to the Pakistani government about his proliferation activities, North Korea received centrifuge cascade designs from Khan Research Laboratories in the 1990s dedicated to making LEU,[23] which may be the one employed at the Yongbyon plant. Subsequently, ISIS confirmed that that each cascade held 344 centrifuges, for a total of 2,064 centrifuges in the Yongbyon plant.

[21] *Taking Stock: North Korea's Uranium Enrichment Program*, op. cit.
[22] The information was in a letter from A.Q. Khan that was found by authorities at the South African firm Tradefin Engineering.
[23] *Taking Stock: North Korea's Uranium Enrichment Program*, op. cit. See also Albright, *Peddling Peril*.

There is little information about the operation of this plant since the fall of 2010. North Korea reported late last year that the plant had start-up problems, citing defects in the facility and North Korea's inexperience in operating a centrifuge program. But North Korea did not provide details about how the plant is experiencing problems. These problems affect, possibly significantly, estimates and projections of enriched uranium production.

While North Korea has said that the plant is for producing LEU for use as fuel in the LWR program, the enrichment plant could be used to make weapon-grade uranium (WGU, 90 percent uranium 235) for nuclear weapons. In fact, the method to produce WGU using designs developed by KRL involves step-wise production of WGU, where the step devoted to the production of LEU requires about 70 percent of the total number of centrifuges to make weapon-grade uranium. As is the case with Iran's Natanz Fuel Enrichment Plant, the 3-4 percent LEU that North Korea may be producing at the Yongbyon plant is nearly 70 percent of the enrichment effort towards making weapon-grade uranium for nuclear weapons. North Korea can further enrich its stock of LEU to weapon-grade relatively quickly either at the Yongbyon facility or at a smaller finishing plant located elsewhere.

This scenario can be better understood by considering an example of KRL's step-wise design. The WGU-production cascade design that Khan sold to Libya comprised 5,832 P2 centrifuges divided into four steps. It was designed to produce about 100 kg of WGU per year.[24] The first step enriches natural uranium up to 3.5 percent; the second step enriches from 3.5 percent to 20 percent; the third takes the material from 20 percent to 60 percent; and the final step enriches the 60 percent material to 90 percent, or weapon-grade. The first step consists of almost 4,000 centrifuges, or nearly 70 percent of the total number of centrifuges used.[25]

By scaling this stepwise design, North Korea could use the 2,000 P2 centrifuges at the Yongbyon plant as part of a 3,000-centrifuge system to make WGU. To do so, it would need an offsite plant with about 1,000 P2 centrifuges to enrich the 3.5 percent material produced at Yongbyon up to WGU. In this system, as mentioned above, the bulk of the enrichment effort would occur at the 2,000-centrifuge Yongbyon plant.

North Korea could also use the Yongbyon plant to make weapon-grade uranium. It could convert some of the cascades to higher enrichment production or first make sufficient LEU and then enrich stepwise to WGU in the same cascades or re-organized ones that would enrich more efficiently than the original cascades.

[24] See Albright, *Peddling Peril* (New York: Free Press, 2010).

[25] The first step contained a total of 3,936 centrifuges enriching natural uranium to 3.5 percent enriched uranium. The second step, composed of 1,312 centrifuges, enriched the 3.5 percent uranium to 20 percent. The third step with a total of 546 centrifuges enriched from 20 percent to 60 percent material. The fourth step, containing only 128 centrifuges, enriched the 60 percent material to 90 percent, or weapon-grade.

In practice, achieving nominal production values of WGU can be difficult. Inefficiencies and other problems in operating centrifuge cascades inevitably lower annual WGU production from nominal values.

Other Centrifuge Plants

Few believe North Korea's statement that the Yongbyon centrifuge facility is its first or only plant because of how quickly North Korea outfitted this building with a centrifuge plant. The plant did not exist in this building at Yongbyon as of April 2009, when the Six Party Talks' disablement process ended. It is possible that North Korea built another plant previously and either transferred the capability to Yongbyon or simply built the Yongbyon facility based on its experience of bringing an original, perhaps smaller, plant into operation. For years, U.S. intelligence agencies have posited that North Korea had another centrifuge plant. Some even assert that this plant had produced WGU as early as the mid-2000s.[26]

The Yongbyon centrifuge plant is likely part of a larger gas centrifuge complex with other facilities at Yongbyon, elsewhere in the vicinity of Yongbyon, or in other parts of the country. ISIS has discussed the full range of facilities elsewhere.[27] In any case, the size of other sites housing centrifuges is at issue. Did North Korea have only a pilot plant, or did it have another production-scale plant?

Few doubt the need for a pilot plant and most would expect that one has existed. The evidence, and arguments for another centrifuge plant are more debatable but nonetheless credible. The large procurements in the 2000s suggest a much larger centrifuge program than represented at Yongbyon. Libya ordered 10,000 P2 centrifuges from the Khan network with the intention to build a 6,000-centrifuge plant. Given that North Korea is believed to have sought enough components for 10,000 centrifuges, it could have planned on operating 6,000 P2 centrifuges in production-scale plants. In addition, North Korea has a military-first policy, and North Korean missile experts were the first ones who acquired the centrifuge technology from Khan Research Laboratories while working there starting in the 1993-1995 period. The North Koreans taught the Pakistanis about building missile components in the Khan Laboratories' centrifuge workshop, where the North Koreans also learned about making P2 centrifuges, according to Khan's 2003 statement. These factors would support that the first centrifuge plant was military in nature and remains secret.

However, there are plausible explanations that the Yongbyon plant is North Korea's first production-scale plant. One explanation is that prior to 2009, North Korea produced only centrifuge components and sub-assemblies for one or two production-scale plants, a major feat in any case. It then shipped components to the Yongbyon site with final centrifuge assembly in a neighboring building close to the current enrichment facility. The period of one and a half years would then be sufficient for refurbishing the building, installing the cascade pipe work and the feed and withdrawal equipment, and assembling

[26] *Taking Stock: North Korea's Uranium Enrichment Program*, op. cit.
[27] *Taking Stock: North Korea's Uranium Enrichment Program*, op. cit.

and installing the centrifuges. This explanation is credible, particularly given the well-known types of delays that can happen in centrifuge programs in developing countries, where the centrifuges have proven harder to build than commonly expected and shortages in goods can create bottlenecks in centrifuge plant deployments. North Korea, like many countries, has depended extensively on overseas assistance to obtain centrifuge technology and the necessary goods. Moreover, North Korea may have planned on a steady stream of technical assistance from the Khan network and was set back by the unexpected busting of the Khan network in 2003.

Estimates of North Korea's production of enriched uranium remain highly uncertain. In addition, the existing available evidence is so sketchy about North Korea's centrifuge program status and history that it is not possible to conclude with certainty that another production-scale plant exists or existed in the past, let alone that North Korea has produced a significant quantity of WGU in such a plant. Despite these reservations, it remains possible that North Korea has already produced WGU in a secret centrifuge plant.

Enrichment Scenarios

To better understand the amount of WGU that North Korea could have produced, ISIS developed a range of possible scenarios that attempt to capture the available information, keeping in mind the lack of confirmed information. In particular, whether North Korea has produced WGU is controversial. Most agree with North Korea's declaration that the Yongbyon centrifuge plant, at least through early 2012, likely did not make WGU. The reason is that North Korea agreed to suspend operations there and allow monitoring by the IAEA, which would relatively easily detect if WGU had been produced and expose North Korea's deception.

The following five scenarios capture the range of North Korea's total WGU production through 2011. In all but one of the scenarios below, it is assumed that North Korea built and operated a smaller-scale pilot gas centrifuge plant with about 300 to 1,000 gas centrifuges for research and development purposes prior to developing a production-scale facility. The pilot plant is assumed to have produced at most small quantities of weapon-grade uranium. In these scenarios, ignoring the centrifuges in a pilot plant, the estimated total number of enriching centrifuges is capped at 4,000. The reason is an ISIS judgment about the difficulty of building and getting large numbers of centrifuges to enrich uranium consistently.

The five scenarios are:

1. North Korea has only one production-scale centrifuge plant that it started in late 2010 and has until today made only LEU. This scenario is North Korea's declaration. [A sub-scenario is that North Korea had an earlier production-scale centrifuge plant that did not produce much enriched uranium. In this case, all centrifuges could have been moved to Yongbyon.]

2. North Korea brought on-line a pilot plant that produced both LEU and HEU in small quantities prior to 2009, but the Yongbyon centrifuge plant is the only production-scale plant. The Yongbyon plant has produced LEU only. The assumption in this scenario is that North Korea could have produced kilogram quantities of weapon-grade uranium and tens of kilograms of LEU and HEU, where the HEU is enriched mainly between 20 and 60 percent in uranium 235. In subsequent discussions, the production of intermediate enriched uranium is ignored.[28]

3. North Korea operates two production-scale centrifuge plants today, the first of which started in the first sub-scenario in 2005 and the second sub-scenario in 2008 and contained about 2,000 gas centrifuges. The first plant is assumed to have produced both LEU and WGU. The second one is the Yongbyon centrifuge plant, which is assumed to have made LEU only. The sub-scenario with a start date of 2005 is deduced from public information about the start of such a plant in a worst-case assessment of the CIA in the fall of 2002.

4. North Korea ran two production-scale plants sequentially, starting the first one in about 2005 and having 2,000 P2 centrifuges. In this scenario, the first plant halted operations in 2009 and the centrifuges were moved to Yongbyon. The first plant made both LEU and WGU. Afterwards, the Yongbyon plant made only LEU. In this case, sampling at Yongbyon would likely reveal any earlier HEU production.

5. North Korea developed a production-scale facility, starting in either 2005 or 2008, containing 3,000 gas centrifuges. North Korea moved approximately 2,000 of these centrifuges to the Yongbyon facility in 2009, where it uses these centrifuges to produce LEU. The remaining 1,000 centrifuges at the first production scale facility have acted as a finishing plant, producing HEU from LEU feedstock enriched at the Yongbyon site. In this scenario, the centrifuge plants did not produce LEU for the light water reactor under construction at Yongbyon. As such, it should be viewed as an upper bound.

There are other scenarios. For example, Pakistan could have sold North Korea WGU in the 1990s, when North Korea sold ballistic missile technology and components to Pakistan, and A.Q. Khan provided centrifuge technologies and components in return. Corruption was great enough in Pakistan at the time that a sale of WGU cannot be dismissed, although the chances that it happened are low. Moreover, China provided Khan with 50 kilograms of WGU in the early 1980s, and Khan may have believed that selling WGU to North Korea was legitimate, despite his denials.

However, in terms of estimating domestic WGU production, these five scenarios provide a reasonable range for an estimated stock of WGU. When additional information is obtained, these scenarios will be adjusted.

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[28] It should be noted that the production of WGU requires the production of LEU and a range of levels of enrichment termed HEU. However, in these estimates, only potential WGU quantities are estimated. Any proposed verification arrangement would also need to assess this enriched uranium as well.

Major Uncertainties. It is important to emphasize the uncertainty surrounding North Korea's potential production of significant quantities of WGU. Statements that it has done so, or for that matter, not done so warrant skepticism in the absence of convincing proof. Thus, these five scenarios represent possibilities at this time.

Moreover, some scenarios appear more or less likely. The first scenario appears unlikely given the widely expected need for a pilot plant to develop centrifuges, particularly production-scale cascades. Although scenario 1 appears unlikely, scenario 2 is credible, where North Korea rapidly built its first production-scale plant in 2009 and as of the end of 2011 had not made any WGU.

Major uncertainties are whether Iran has a production-scale plant other than the one at Yongbyon, and if it does, the date when it started. A start date earlier than 2005 for a production-scale plant appears less likely given the difficulty in establishing operational centrifuge plants and the absence so far of more proof of such a start date. According to a European centrifuge expert who intensively studied the Khan network, Pakistan provided the first nine of an original order of 25 P2 centrifuges in 1999. This source said that the rest of the P2s in this order were not provided. With an initial supply of P2 centrifuges arriving in 1999, North Korea would have had to work extremely fast to have a centrifuge plant of a few thousand centrifuges functioning effectively by 2005, let alone earlier.

Another central uncertainty that is related to the number of production-scale plants is the lack of information about the number of P2 centrifuges North Korea has built and operated. Procurement information suggests that North Korea could build thousands of P2 centrifuges. Here, the limit is taken as 4,000 operating P2 centrifuges as the maximum number it could have brought into operation in centrifuge plants through 2011. The main reason, as discussed above, is the difficulty developing countries have bringing large numbers of centrifuges into operation.

A third uncertainty is how consistently these centrifuges have operated. The effect of this uncertainty is incorporated into the estimates of weapon-grade uranium production discussed below.

WGU Production Rates

Estimating the amount of weapon-grade uranium produced in a North Korean centrifuge plant is fraught with difficulties. This section develops three WGU estimates that provide a range of values. These WGU production rates are lower than one typically predicted by a separative work calculator. But an estimate based on a separative work calculator in essence assumes one long ideal cascade producing WGU in one step from natural uranium to weapon-grade uranium. Such a long cascade of P2 centrifuges is generally not deployed for practical reasons, since it would require a very large number of centrifuges. A cascade can fail, thus risking the viability of all centrifuges in the cascade, and this has led centrifuge designers to install cascades with a smaller number of centrifuges connected with fast-acting valves. On the other hand, forming centrifuges into shorter cascades increases the level of inefficiency. In addition, it is known that the

Pakistani centrifuge plants, which used the P2 centrifuges, had operational problems that North Korea is likely to also experience that caused an increase in inefficiencies compared to the operation of ideal cascades. Therefore, actual WGU production is often significantly less than what is indicated by a separative work calculator.

The first or upper bound estimate is derived from information uncovered during the investigation of the Khan network. As discussed above, these investigations revealed that A.Q. Khan stated that the optimal output of Libya's centrifuge plant organized into four steps containing 5,832 P2 centrifuges would be about 100 kg of WGU per year, where the mass is measured in terms of uranium.[29] Scaling to a 2,000 P2 centrifuge plant would result in an output of 34 kg of WGU per year, assuming that the cascades to make HEU can be adjusted in size accordingly. For later calculation purposes, this value is normalized to 17 kg of WGU per year per 1,000 P2 centrifuges.

To account for the possibility that the quantities of WGU would likely be lower, particularly in the first several years of operating a production-scale centrifuge plant, two additional methods of assessing WGU production are used. Both methods are based on the four-step plant design provided by Khan to Libya but have lower efficiencies than Khan's estimate.

The lower bound is based on an analysis conducted by one of the authors about the Yongbyon plant and a secret 1,000 P2 centrifuge topping plant, giving a total of 3,000 P2 centrifuges. This assessment involves a highly inefficient four-step process leading to very high losses in the upper two steps. After normalization, this estimate results in 4.17 kg weapon-grade uranium per year per 1,000 P2 centrifuges. This estimate symbolizes a plant that is having severe operational problems. Nonetheless, it could be an accurate representation of the actual situation particularly during the first several years of operation. North Korea would be expected to improve this rate of production with continued operation.

The other estimate is based on another centrifuge expert's analysis of the Yongbyon plant's capability to make WGU that involves reconfiguring some of the existing cascades. It starts with a known feed quantity based on the P2 centrifuge design. Based on these values, it uses a separative work calculator to derive the product in each of the four steps. Moreover, this method assumes that North Korea produces WGU in a 2,000 P2 centrifuge plant composed of six cascades containing 344 centrifuges. After producing 4 percent LEU for a few years, the plant starts producing 20 percent LEU in a subset of these cascades. After almost another year, some of the cascades are modified to produce WGU from 20 percent LEU in two steps. In about four years, this method results in the production of about 100 kg of WGU. This method can also be applied over a shorter time period with the result that the amount of WGU would be proportionally less. After normalization, this estimate becomes 11.3 kilograms of weapon-grade uranium per year

[29] See Albright, *Peddling Peril*.

per 1,000 P2 centrifuges.[30] This estimate represents a plant operating well, but less than optimally.

In summary, the three WGU production estimates are:

1. 4.17 kg WGU per year per 1,000 P2 centrifuges
2. 11.3 kg WGU per year per 1,000 P2 centrifuges
3. 17.0 kg WGU per year per 1,000 P2 centrifuges

These three values are applied to the scenarios. Table 1 shows the results of these estimates. The amounts vary greatly, from 0-332 kilograms of weapon-grade uranium, reflecting the large uncertainties in these estimates.

In scenarios 1 and 2, either WGU is not produced or only relatively small quantities are produced. In scenario 2, where some WGU could be produced, it is likely less than the amount needed for a nuclear weapon, namely less than 15-25 kilograms of WGU.

In scenarios 3, 4, and 5, a secret centrifuge plant is posited to exist but the number of centrifuges and the plant's start-up date varies. In all three scenarios, one obtains enough WGU for at least one nuclear weapon. Thus, if North Korea built a clandestine plant, and can make up to a total of 3,000-4,000 P2 centrifuges, then reasonable scenarios predict the production of at least enough for one to several nuclear weapons. In these three scenarios, the upper bounds vary from 136-332 kilograms of WGU, depending on the number of centrifuges and the date when the plant achieved operational status.

If a secret plant started in 2008, then the results vary between 33 and 204 kilograms of WGU. If the start date was 2005, then the results fluctuate between 54 and 332 kilograms of WGU. The lower estimates are similar in scenarios 3 and 4, 33 vs. 38 kilograms. Scenario 3 with a secret plant starting in 2008 and containing 2,000 centrifuges produces a range of 33-136 kilograms of WGU. Scenario 5 with a secret plant starting in 2005 and having 3,000 centrifuges produces a range of 81-332 kilograms of WGU, the most extreme case.

However, it is necessary to reiterate that the public evidence for a secret plant with 2,000-3,000 centrifuges remains uncertain. Building and operating a gas centrifuge plant in North Korea could take considerably longer than expected by Western standards.

It is a matter of speculation about how North Korea would use WGU in nuclear weapons. It could use the WGU to fashion fission weapons similar, albeit necessitating more fissile material and a larger warhead design, to its plutonium-based fission weapons. It could also use the WGU in designing thermonuclear explosive devices, e.g. the device's

[30] This estimate assumes a greater separative work output of each P2 centrifuge than four swu per year per centrifuge. After normalization, this estimate becomes 12.94 kilograms of weapon-grade uranium per year per 1,000 P2 centrifuges. This value is reduced by about 13 percent to account for the lower average P2 separative output of four swu per year, resulting in a value of 11.3 kilograms of weapon-grade uranium per year per 1,000 P2 centrifuges.

secondary. Lastly, North Korea could use WGU in conjunction with plutonium to seek fission, or possibly boosted, weapons, with a significantly greater explosive yield.

If the WGU were used in a crude fission weapon without any plutonium, then North Korea would likely need less than a significant quantity of WGU. How much less is unclear, but 15-25 kilograms per weapon would likely include many possible weapons designs, where a midpoint of 20 kilograms per weapon is selected in these calculations. In the scenarios considered, the range is broad, from 0 to almost 17 weapons' worth of WGU. A later section discusses this range in more detail. But as can be seen, the existence of a secret centrifuge plant would mean that North Korea could have enough WGU for nuclear weapons. In the lower bound, where the plant is assumed to work poorly, it would have enough WGU for 1-4 nuclear weapons. The upper bound estimate would give North Korea enough WGU for 6-16 weapons.

Future Production of WGU and Weapon-Grade Plutonium

Although questions about past WGU remain, few doubt North Korea's capacity to make WGU. At the least, North Korea could reconfigure the Yongbyon plant to make WGU, or it could build more centrifuges to outfit another centrifuge plant. If the centrifuge cascades work reasonably well, North Korea could accumulate significant quantities of WGU during the next several years. However, it should be noted that North Korea has not stated that it is making WGU at this time or that it is planning to do so in the near future.

It is instructive to first consider the case where North Korea produces WGU over the next five years, from the start of 2012 through 2016, while making no LEU for the LWR. Despite the likely lack of realism in this case, it represents an upper bound on WGU production over the next several years. If North Korea makes LEU for the LWR, as expected, these WGU values would be significantly lower. This modified case is discussed below.

In this illustrative case, two basic scenarios are used: (A) the Yongbyon plant is the only centrifuge plant but it started producing WGU using 2,000 P2-type centrifuges in the beginning of 2012 and, (B) the Yongbyon plant and a secret production-scale plant, each with 2,000 P2 centrifuges, have produced WGU in tandem since the start of 2012. To reflect expected growth in North Korea's centrifuge program, starting in 2014, each year 1,000 P2 centrifuges are added to the total of each scenario. Scenario A, for example, would have a total of 3,000 centrifuges in 2014, and scenario B would have 5,000 total centrifuges in 2014.

Table 2 contains these estimates of stocks of WGU produced from the start of 2012 through 2016, presented cumulatively. The estimates utilize the same WGU production estimates as discussed above. A mid-range is estimate 2, where the centrifuge plant(s) are expected to work reasonably well. To arrive at total production of WGU, these values will later be added to those in table 1.

In scenario A, stocks of WGU slowly build up. In addition to depending on the numbers of centrifuges, the exact amount of WGU will depend on the types of problems encountered in operating centrifuge cascades. The projected range of WGU varies from 8-34 kilograms of WGU by the end of 2012, or enough for 0-1 nuclear weapons. By the end of 2016, North Korea could have enough WGU for 67 to 272 kilograms of WGU, or enough for 3 to 13 nuclear weapons.

Under scenario B, the growth of WGU would be more rapid. By the end of 2012, North Korea could have enough WGU for 17-68 kilograms of WGU, or enough for 0-3 nuclear weapons. By the end of 2016, it would have 108-442 kilograms of WGU, or enough for 5-22 nuclear weapons.

If North Korea brings into operation the LWR at Yongbyon by the end of 2013, it will need to have produced a considerable amount of LEU for this reactor, lessening capacity to make WGU. In addition, for the reactor to start in 2013, the Yongbyon centrifuge plant would have had to work well. In these estimates, annual 3.5 percent LEU requirements would be expected to require all of the Yongbyon centrifuge plant's output until 2013, at which point the plant could start making WGU. If the plant does not work well, then it would not be able to make enough LEU to start the LWR until 2014 or 2015, assuming that only the Yongbyon plant produces 3.5 percent LEU.

If the LWR were to use 10-20 percent LEU in driver fuel, North Korea will need to create or dedicate some additional enrichment capacity to the production of the fuel. However, this extra capacity would allow for a significant increase in the number of plutonium-based nuclear weapons using a tested design. Thus, if North Korea must make LEU for the LWR, it may decide to produce driver fuel to make weapon-grade plutonium. To sustain production of driver fuel, North Korea is estimated to need to have more enrichment capacity than the Yongbyon centrifuge plant currently has, perhaps up to another 1,000 P2 centrifuges in operation. But North Korea has enough time to install this extra capacity, and the estimates above assume that North Korea would do so in 2014.

In the case that supposes that the Yongbyon plant must make 3.5 percent LEU fuel for the LWR, its production of WGU would be less. Table 3 lists rough numerical estimates of WGU production, after subtracting LEU requirements for the LWR under scenarios A and B. At best, in the case of scenario A, North Korea could make enough WGU for 2-3 nuclear weapons by the end of 2016. North Korea could make sufficient amounts of driver fuel, allowing the production in 2015 and afterwards of enough plutonium for 4-10 nuclear weapons per year, where the total annual reactor production is estimated as 20 kilograms of weapon-grade plutonium, and each weapon is assumed to require 2-5 kilograms of weapon-grade plutonium (see above). A second enrichment site, under scenario B, could allow for substantial production of WGU while the Yongbyon one would produce driver fuel for the LWR. By the end of 2016, North Korea could produce enough WGU for 3-17 nuclear weapons, less than the maximum number but still a substantial amount.

Cumulative Stocks of Fissile Material and Their Weapons-Worth

Since both plutonium and WGU can be used in nuclear weapons, this section assesses the total number of nuclear weapons North Korea could build from these materials. To simplify the discussion, midpoints of WGU production estimates with associated ranges are used. Estimate 2 is the midpoint for WGU production, or 11.3 kg WGU per year per 1,000 P2 centrifuges. The lower and upper bound of the associated range is defined by estimates 1 and 3. A fission nuclear weapon made with WGU is assumed to require 20 kilograms of WGU.

Table 4 lists the results through the end of 2011. As can be seen, the central estimate is that as of the end of 2011, North Korea has enough fissile material for 12 to 23 nuclear weapons. Assuming the existence of a secret centrifuge production-scale plant and ignoring the high end WGU estimate, the central estimates of the number of weapons cluster in the range of 16-19 nuclear weapons worth. If no WGU were produced through 2011, the central overall value remains at 12 nuclear weapons worth, where the weapons involve only plutonium.

It is illustrative to predict fissile material estimates through 2016 using the mid-point estimates only without considering the range. Table 5 compares three cases of projected nuclear weapons production through 2016. The date of 2016 is used here as above. This date also allows for the development of weapon-grade plutonium production in the LWR.

The three cases are:

1. North Korea does not make any more plutonium for weapons, but it produces LEU for the experimental LWR;
2. It optimizes the LWR for making weapon-grade plutonium; and,
3. It does not provide LEU to the LWR, but instead dedicates centrifuge capacity to making WGU.

Scenarios A and B are as defined above and in table 2, namely scenario A assumes one centrifuge plant at Yongbyon and scenario B assumes two centrifuge plants.

As expected, all of these projections, which are shown in table 5, show an increase in North Korea's nuclear weapons arsenal. They also show that dedicating a significant portion of the centrifuge capacity to allowing the LWR to make weapon-grade plutonium does not cause a reduction in the total number of projected North Korean nuclear weapons, compared to dedicating all the centrifuge capacity to making WGU and not making any LEU for the LWR. However, this strategy does delay the attainment of those weapons.

Case 1 This case shows that absent the LWR making plutonium for nuclear weapons, North Korea's projected growth in its nuclear arsenal will be relatively modest. The reactor's requirement for LEU would reduce significantly the ability of North Korea to make WGU for nuclear weapons. In scenario A, the estimated number of weapons at the end of 2016 is 14-25, an increase of two weapons since the end of 2011. The scenario B estimate is higher but still represents a modest increase of eleven weapons in North Korea's nuclear arsenal to 23-34 nuclear weapons. This growth represents an average increase of about two weapons per year from the end of 2011 to the end of 2016.

Case 2 Under case 2, North Korea's rate of weapon-grade plutonium production would far exceed the rate of plutonium production in the 5 MWe reactor at Yongbyon, although new production would not be expected until about 2015. To produce plutonium at this accelerated rate, as in case 1, much of the North Korea's enrichment output would be applied to making enriched uranium driver fuel for the LWR.

Under scenario A in case 2, North Korea would likely have enough enrichment capacity to produce a limited amount of weapon-grade uranium for advanced nuclear weapons. By the end of 2016, North Korea is projected to have 28-39 nuclear weapons, or an increase of 16 weapons since the end of 2011, all but one produced in 2015 and 2016.

Under scenario B in case 2, which allows for a second centrifuge plant, North Korea could produce a much larger quantity of WGU. It could have 37-48 nuclear weapons, or an increase of 25 weapons, most of which are produced in 2015 and 2016.

Under case 2, the LWR would be an efficient way to significantly increase the number of North Korea's nuclear weapons using plutonium while leaving enough enrichment capacity to make weapon-grade uranium for more advanced nuclear weapons. However, the downside is that weapons production would be delayed by several years as the LWR comes into operation.

Case 3 If the LWR is dedicated to making weapon-grade plutonium for weapons, in the longer term North Korea could produce more nuclear weapons using this route than if it dedicated its centrifuge capacity to making WGU and not producing any LEU for the LWR, which is described in case 3. However, this result must be tempered by the fact that the difference would be less if instead of 20 kilograms of WGU per weapon, only 15 kilograms of WGU were needed per weapon, something which may be possible for North Korea to do. Thus, given such uncertainties the relative differences between cases 2 and 3 should not be overly emphasized.

The results of cases 1, 2, and 3 can also be understood by comparing these cases in each of scenarios A and B. Figure 4 shows the growth in the arsenal under scenario A where the mid-points of the ranges in table 5 are plotted. This simplification is needed to make a coherent graph but it does not change the trends in the graphs. In case 2, displayed in blue, the graph shows a dramatic increase in the numbers of weapons after 2014, reaching a value at the end of 2016 that exceeds the value in case 3, the green line, which provides a baseline where the centrifuge capacity produces only WGU and does not produce LEU for the LWR.

Figure 5 plots the mid-points from table 5 for scenario B, which shows a steady increase in the number of weapons in both cases 1 (red) and 2 (orange). The jump in the values in

2015 and 2016 under case 2, scenario B, is still pronounced compared to the baseline case 3 (teal).

Figure 4: Midpoint Estimates of Projected Weapons Worth in Scenario A, which assumes only one centrifuge plant, 2011 – 2016

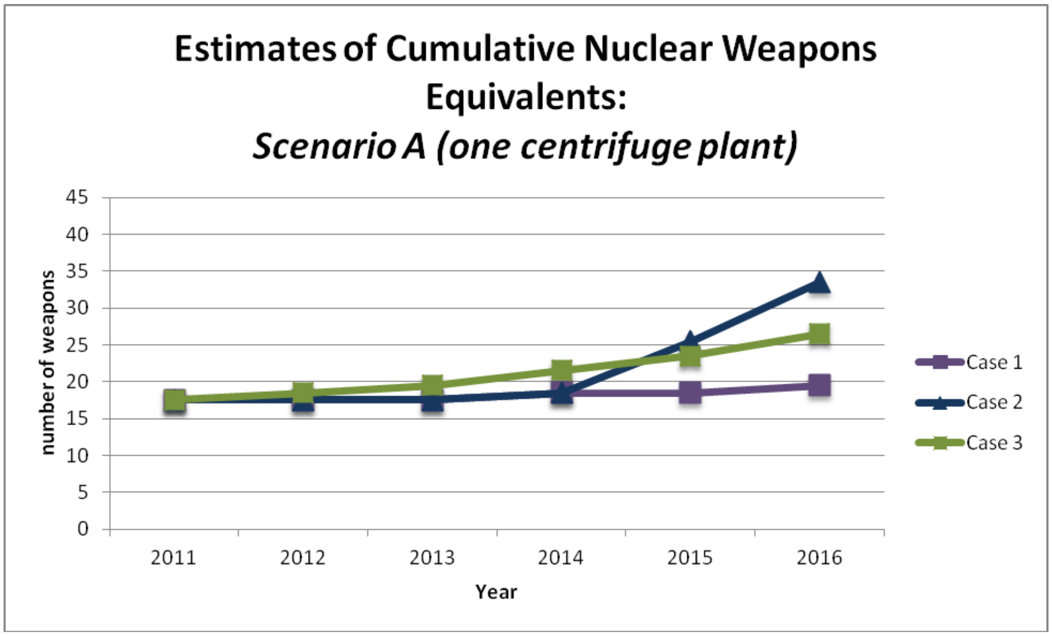
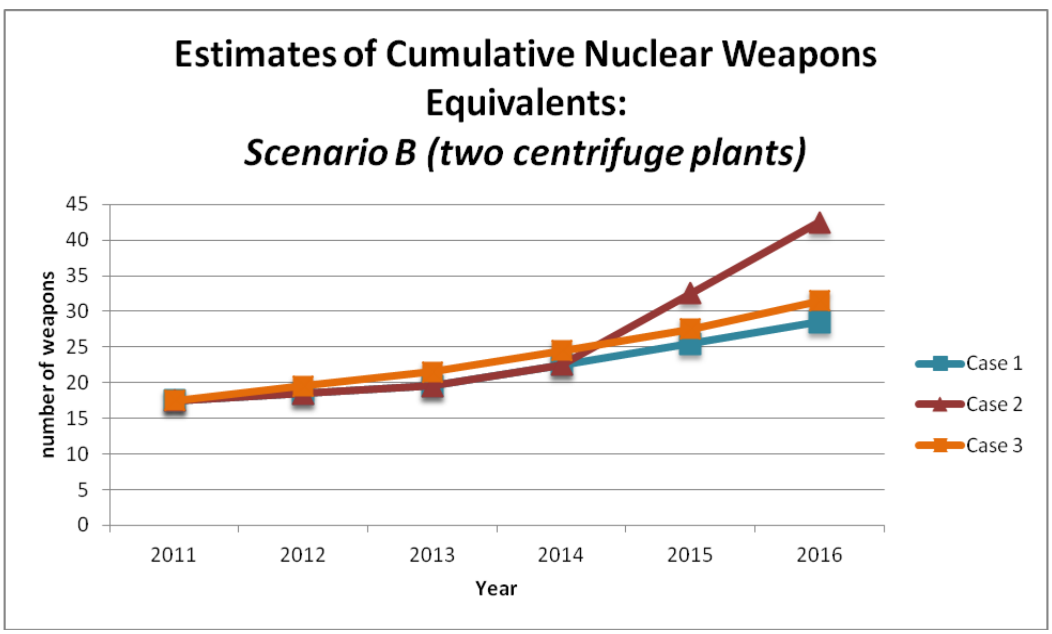


Figure 5: Midpoint Estimates of Projected Weapons Worth in Scenario B, which assumes two centrifuge plants, 2011 – 2016



Thus, North Korea can maximize its capacity to expand its arsenal using its enrichment capabilities by creating a driver fuel system in a LWR to produce plutonium. Although it is not the most efficient use of North Korea's enrichment efforts, because a significant quantity of plutonium is so much smaller than a significant quantity of uranium, such an approach yields the greatest results in terms of weapons produced. Furthermore, North Korea could use an existing weapons design in this scenario and avoid problems with miniaturization of a new device. However, this scenario assumes a number of things about North Korean motivations and technological capabilities. All scenarios indicate that regardless of North Korea's specific choices over its nuclear program, the uranium enrichment program offers it the capacity to significantly, and likely sustainably, expand its arsenal.

Findings and Recommendations

The results of this report appear dominated by uncertainties, particularly concerning the amount of weapon-grade uranium North Korea possesses and its ability to build and successfully operate the LWR.

North Korea's development of gas centrifuges provides flexibility in its planning for building nuclear weapons while allowing for more advanced nuclear weapons. Combined with the construction of an LWR, the centrifuge program provides North Korea with the capability to greatly expand its nuclear arsenal and build more advanced nuclear weapons. On the other hand, the scenario that yields the greatest number of weapons requires North Korea to take a significant technological risk using interlocking LWR and centrifuge programs.

Despite North Korea's development of gas centrifuges, a credible lower bound on WGU production through 2011 is near zero. The Yongbyon centrifuge plant could be its first one, although it likely also operated a pilot plant elsewhere.

If a second enrichment plant exists, North Korea could have made a substantial amount of WGU. A credible upper bound is enough WGU for a dozen or more nuclear weapon equivalents. While possible, this worst-case scenario is particularly fraught with uncertainty.

It remains unconfirmed if North Korea is making WGU today. However, it could be doing so, even if it possesses only the Yongbyon centrifuge plant. By the time period 2015-2016, it could produce a significant amount of WGU.

Currently, North Korea's plutonium inventory appears capped, with enough for 6-18 nuclear weapons and a midpoint of 12 nuclear weapons. It could add marginally to this number if it restarted its 5 MWe reactor at Yongbyon.

If the experimental LWR does not make plutonium for nuclear weapons, the reactor's requirement for LEU would significantly reduce North Korea's ability to use its enrichment program to make WGU for nuclear weapons. However, the experimental light water reactor could be designed to optimize the production of weapon-grade plutonium for nuclear weapons. This approach would allow North Korea to utilize its existing family of plutonium-based nuclear weapons designs. Its rate of production of weapon-grade plutonium could far exceed the rate of plutonium production in the 5 MWe reactor at Yongbyon, although separated plutonium would not be expected until about 2015. To produce plutonium at this accelerated rate, much of the North Korea's enrichment output would be applied to making enriched uranium driver fuel for the LWR, particularly if the Yongbyon centrifuge plant is its only production-scale plant. However, in scenario A, North Korea would likely retain enough enrichment capacity to produce a limited amount of weapon-grade uranium for advanced nuclear weapons. Under scenario B, which allows for a second centrifuge plant, North Korea could produce a much larger quantity of WGU. The LWR could thus be an efficient way to significantly increase the number of North Korea's nuclear weapons using plutonium while leaving enough enrichment capacity to make weapon-grade uranium for more advanced nuclear weapons. If the LWR is dedicated to making weapon-grade plutonium for weapons, in the longer term North Korea could produce more nuclear weapons using this method than if it dedicated its centrifuge capacity to making WGU and not producing any LEU for the LWR. However, the downside is that weapons production would be delayed by several years as the LWR comes into operation.

With such large uncertainties, a central challenge is learning more about North Korea's nuclear program and its intentions. There is a great need to better understand North Korea's actual accomplishments in its centrifuge program. The upper bound estimates of current WGU stocks and projected stocks of fissile materials and nuclear weapons in particular risk increasing concern about the North Korean nuclear threat, which could spark over-reactions if these estimates turn out not to be realistic. A priority is thus determining whether there is a secret centrifuge plant in addition to the Yongbyon centrifuge plant, how many P2-type centrifuges in total have been deployed successfully, and how well have these centrifuges operated. In addition, can North Korea produce enough LEU for the LWR? What is the design of the LWR core, and will it make plutonium for nuclear weapons?

Regardless of the accuracy of the upper bound estimates, it is critical to take steps that reduce the chances that North Korea will increase the size of its nuclear arsenal. In essence, the United States and its allies should develop measures today to head off this future potential threat. This strategy should include both an attempt to negotiate a solution and increase efforts to detect, thwart, and delay North Korea's nuclear progress.

The approach of achieving pre-steps as a precondition for the resumption of the Six Party Talks remains a useful way to cap the DPRK's uranium enrichment program and head off the use of the LWR to make weapon-grade plutonium. As such, negotiations should attempt to re-establish this approach after a consideration of the needed reforms in pursuing this negotiating path. Pre-steps concerning the LWR need to be added. In particular, North Korea should commit not to use any domestically produced LEU in the LWR. This commitment would parallel a step to implement a moratorium on operations at the Yongbyon centrifuge plant. In addition, North Korea should also commit not to use the LWR to make plutonium for nuclear weapons and not to reprocess any of the LWR's irradiated fuel. The process of achieving pre-steps needs to be more transparent to provide greater certainty of the DPRK's commitments. One improvement would be if the negotiations produced written agreements that could be publicly released. A more open approach would make it more difficult for North Korea to re-interpret or deny the existence of parts of an agreement later.

If negotiations resume, the issue of the experimental LWR should be taken up. As an incentive, the international community could offer North Korea 3-4 percent LEU fuel for this LWR, subject to the conditions that it would never use domestically produced LEU and the supplied LEU, after irradiation and cooling, would be returned to the supplier.

Looking again into the future, North Korea's centrifuge program poses several complicated challenges to establishing a uranium enrichment program (UEP) disablement and verification regime, in particular (1) gaining assurance in the completeness of a North Korean list of centrifuge facilities subject to disablement, and (2) verifying a declaration of the total amount and type of enriched uranium produced in the enrichment program. The United States should start now to carefully prepare for these verification and negotiation challenges.

Absent the pre-steps and successful negotiations, the United States should draw on experiences and lessons of efforts to understand and delay Iran's nuclear program. These efforts have been aimed at better characterizing its secret centrifuge facilities and activities and developing methods to thwart or delay progress in the centrifuge program.

Like Iran, North Korea remains dependent on foreign supply for its centrifuge program and its procurements for this program are on-going. However, they are currently difficult to detect, let alone stop. China stands out as an important platform from which North Korea mounts its smuggling operations for its centrifuge programs. North Korea uses its smuggling networks in China to acquire a range of dual-use items necessary for its centrifuge program from both Chinese private companies and high-tech foreign suppliers. Similar to Iran, North Korea likely needs the high-quality goods for its centrifuge program that companies in Europe and the United States produce and that many sell in China. Foreign suppliers in China are especially vulnerable to exploitation by North Korean smugglers and their agents, particularly Chinese private companies posing as false end users for the foreign goods.

China has taken important steps to bolster its laws and practices aimed at stopping illegal exports. Nonetheless, China simply does not do enough to stop smuggling operations put forth by North Korea as well as Iran. China needs to strengthen its export control laws and improve their enforcement. It also needs to support the improvement of U.N. Security Council sanctions that aim to ensure that North Korea cannot acquire goods for its nuclear programs.

To those ends, China should improve its implementation and enforcement of its export control laws and U.N. Security Council sanctions, including expanding the number of centrifuge-related goods that China considers as banned for export to North Korea. China should also take additional steps to make it harder for North Korea to succeed in buying what it needs to maintain and expand its centrifuge program. The United States and Europe have considerable experience in this area and are ready for consultation with China.

The United States already plays an important role in furthering Chinese improvements in the area of trade controls and sanctions implementation with respect to North Korea and Iran. But too often, China downgrades this issue in response to U.S. actions in other areas it does not like, such as arms sales to Taiwan. China does not attach the same priority to this issue as the United States. In response, the United States should continue to address this issue at the highest levels of U.S./Chinese diplomatic and military interaction. China needs to understand that this problem is fundamental to both countries and transcends the normal ebb and flow of issues subject to U.S./Chinese negotiations.

In collaboration with China and other members of the Security Council, the United States should develop a new U.N. Security Council resolution that clarifies and greatly expands the list of goods banned for sale to North Korea's nuclear and missile programs. The new resolution in particular should make it harder for North Korea to succeed in buying what it needs to maintain and expand its centrifuge program.

Although public discussions generally complicate negotiations with China, they can serve to highlight actions that are damaging or counterproductive, giving China additional incentive to address these problems. Keeping all the interactions secret can also shield China against accountability. Thus, the U.S. government should selectively make certain cases and problems public and make clear the desired remedy.

The United States should seek additional cooperation from U.S. industries with subsidiaries in China to detect and thwart DPRK smuggling efforts. It should model this effort on those already being done in Britain and Germany.

The proliferation of gas centrifuge technology, nuclear materials, and dual-use goods such as maraging steel, remains a central concern. As a result, North Korea should be held to past commitments against proliferation. The October 3, 2007 Six Party Agreement on Second-Phase Actions contains a commitment by North Korea "not to transfer nuclear materials, technology, or know-how." In the April 2008 confidential Singapore Minute, North Korea reportedly agreed to cooperate on proliferation activities, in particular by agreeing not to proliferate and to cooperate on the verification of that commitment. A goal should be to strengthen North Korea's non-proliferation commitment by complementing it with a North Korean pledge not to illicitly procure for its own nuclear program or for the programs of other countries or groups. This moratorium on overseas procurement would include nuclear components, raw materials, equipment, or technology for its own or others' centrifuge programs. Absent North Korea's adherence to these commitments, North Korea should be subject to additional U.N. Security resolutions and domestic sanctions legislation that seek to make North Korean proliferation and smuggling more detectable and harder to accomplish.

Final Word

As in many other cases, negotiations are the best way to alleviate the security challenges posed by North Korea's growing nuclear program. They should be pursued vigorously. Absent negotiations, however, the United States has few options than increasing its efforts to make it more difficult for North Korea to make progress on its nuclear weapons programs.

Appendix

Table 1: Estimated Possible Stocks of WGU, through 2011
(LEU and any intermediate enriched stocks of HEU are not included in this table)

Scenario	WGU (kg) Estimate 1	Estimate 2	Estimate 3
1. North Korean declaration (Yongbyon plant only)	0	0	0
2. Yongbyon plant plus pilot plant	kg quantities		
3. Two centrifuge plants: Yongbyon and undeclared one Each with 2,000 P2 centrifuges			
a) Yongbyon LEU only and other made WGU since 2008	33	90	136
b) same as (a) but start of WGU production is 2005	54	147	221
4. Two centrifuge plants, each with 2,000 centrifuges, operating sequentially, first one from 2005 until 2009, when centrifuges moved to Yongbyon. WGU production through 2009; LEU only afterwards	38	102	153
5. Two centrifuge plants, first one with 3,000 centrifuges, 2,000 of which were moved to Yongbyon in 2009 (has operated as a unit to make WGU)			
a. Start date 2008	50	135	204
b. Start date 2005	81	220	332

Note: Although precise figures are given in the table, the accuracy is not nearly as precise. They are given in this way to facilitate comparison.

Table 2: Projected Maximum Cumulative Stocks of WGU produced from the start of 2012 through 2016, end of year. (LEU for the LWR is not produced in this projection)

Scenario	WGU Cumulative (kg)				
	2012	**2013**	**2014**	**2015**	**2016**
A Yongbyon plant only, 2,000 centrifuges in 2012 and 2013, then increasing in 2014 at rate of 1,000 per year					
Estimate 1	8.3	17	29	46	67
Estimate 2	23	45	79	124	181
Estimate 3	34	68	119	187	272
B. Two centrifuge plants: Yongbyon and undeclared one, each with 2,000 P2 centrifuges in 2012 and 2013, then increasing in 2014 at rate of 1,000 per year					
Estimate 1	17	33	54	79	108
Estimate 2	45	90	147	214	294
Estimate 3	68	136	221	323	442

Note on methodology: It is assumed that a full year's worth of WGU can be produced in a single year. This is possible because of the use of a four-step design process. Although precise figures are given in the table, the accuracy is not nearly as precise. They are given in this way to facilitate comparison. (LEU and any intermediate enriched stocks of HEU are not included in this table)

Table 3: Projected Cumulative Stocks of WGU produced from the start of 2012 through 2016 With Reduction to Account for Production of 3.5 Percent LEU, end of year
(LEU and any intermediate enriched stocks of HEU are not included in this table)

Scenario	WGU Cumulative (kg)				
	2012	**2013**	**2014**	**2015**	**2016**
A Yongbyon plant only, 2,000 centrifuges in 2012 and 2013, then increasing in 2014 at rate of 1,000 per year					
Estimate 1	0	0	0	0	0
Estimate 2	0	5	22	38	54
Estimate 3	0	8	32	57	71
B. Two centrifuge plants: Yongbyon and undeclared one, each with 2,000 P2 centrifuges in 2012 and 2013, then increasing in 2014 at rate of 1,000 per year					
Estimate 1	8	17	29	46	67
Estimate 2	23	50	101	162	235
Estimate 3	34	76	151	244	343

Note on methodology: In all cases, 2011 and 2012 are periods when the Yongbyon plant's entire capacity is utilized to produce the initial core of LEU for the LWR. Both estimate 2 and estimate 3 assume that enough LEU is made for the initial core by the end of 2012. Afterwards, each is assumed to produce 3.5 percent LEU at the same rate in the Yongbyon plant. This idealized case assumes that the production of 3.5 percent LEU is done more efficiently than the production of higher enriched uranium. The difference in the resulting estimates arises from different production rates of WGU, which are given in the section on WGU production rates. Although precise figures are given in the table, the accuracy is not nearly as precise. They are given in this way to facilitate comparison.

Table 4 Total Fissile Material Stocks, end of 2011, central estimate with range in parenthesis

	Amount (kg)	Weapons-Worth
Plutonium	34-36	12 (6-18)
Weapon-Grade Uranium		
Scenario 1	0	0
Scenario 2	kg quantities	0
Scenario 3		
a) 2008	90 (33-136)	4 (1-7)
b) 2005	147 (54-221)	7 (2-11)
Scenario 4	102 (38-153)	5 (1-8)
Scenario 5		
a) 2008	135 (50-204)	6 (2-10)
b) 2005	220 (81-332)	11 (4-17)
	Subtotal	**0-11**
	Total	**12-23 (central estimate)**

Table 5: Mid-Range Estimates of Cumulative Nuclear Weapons Equivalents, through 2016

	Cumulative Production of Nuclear Weapons					
	2011	**2012**	**2013**	**2014**	**2015**	**2016**
Case 1: No more plutonium production for weapons but LEU provided to LWR						
Subcase A						
W.G. Plutonium	12	12	12	12	12	12
Pre-2012 WGU	0-11	0-11	0-11	0-11	0-11	0-11
Post-2012 WGU	-	0	0	1	1	2
Total	**12-23**	**12-23**	**12-23**	**13-24**	**13-24**	**14-25**
Scenario B						
W.G. Plutonium	12	12	12	12	12	12
WGU produced to 2012	0-11	0-11	0-11	0-11	0-11	0-11
WGU produced afterwards	**-**	1	2	5	8	11
Total	**12-23**	**13-24**	**14-25**	**17-28**	**20-31**	**23-34**
Case 2: Weapon-grade plutonium production in LWR						
Scenario A						
W.G. Plutonium	12	12	12	12	19	26
WGU produced to 2012	0-11	0-11	0-11	0-11	0-11	0-11
WGU produced afterwards	-	0	0	1	1	2
Total	**12-23**	**12-23**	**12-23**	**13-24**	**20-31**	**28-39**
Scenario B						
W.G. Plutonium	12	12	12	12	19	26
WGU produced to 2012	0-11	0-11	0-11	0-11	0-11	0-11
WGU produced afterwards	-	1	2	5	8	11
Total	**12-23**	**13-24**	**14-25**	**17-28**	**27-38**	**37-48**
Case 3: No LEU provided to the LWR; WGU production only						
Scenario A						
W.G. Plutonium	12	12	12	12	12	12
WGU produced to 2012	0-11	0-11	0-11	0-11	0-11	0-11
WGU produced afterwards	-	1	2	4	6	9
Total	**12-23**	**13-24**	**14-25**	**16-27**	**18-29**	**21-32**
Scenario B						
W.G. Plutonium	12	12	12	12	12	12
WGU produced to 2012	0-11	0-11	0-11	0-11	0-11	0-11
WGU produced afterwards	-	2	4	7	10	14
Total	**12-23**	**14-25**	**16-27**	**19-30**	**22-33**	**26-37**

Notes: In the case of WGU, mid-range production estimates correspond to estimate 2 in the section on WGU production rates. In cases 1 and 2, the production of 3.5 percent LEU is assumed to be done more efficiently than the production of higher enriched uranium. The extra enrichment needed to make driver fuel, compared to 3.5 percent LEU, is not factored into these estimates. The overall effect of this assumption is judged as minimal when comparing the cases, which is the intention of this table.