North Korean Nuclear Facilities After the Agreed Framework[1]

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1. Introduction

North Korea's nuclear program has evolved considerably since 2002, when the Agreed Framework (AF) collapsed and Pyongyang withdrew from the Nuclear Nonproliferation Treaty (NPT). International Atomic Energy Agency (IAEA) inspectors were expelled from Yongbyon in December 2002, and the 5MWe (electric) reactor was restarted in January 2003. In April 2003, North Korea told American officials that it had developed a nuclear deterrent[2]. Yet with no access to the Yongbyon Nuclear Center,[3] it was not possible for the IAEA or the U.S. government to accurately assess the state of facilities or the amount of fissile-materials production at the complex.[4]

In January 2004, a delegation from Stanford University led by Prof. John W. Lewis and joined by one of the authors, Siegfried S. Hecker, at the time senior fellow at the Los Alamos National Laboratory and former director, was invited to visit the Yongbyon Nuclear Center. This visit by Hecker and follow-on visits during each of the next six consecutive years contributed substantially to our knowledge of North Korean nuclear activities. In this report, we utilize information obtained during the Stanford delegation visits, along with other open-source information, to provide a holistic assessment of North Korean nuclear developments from the demise of the AF through November 2015.

The timeline shown in Fig. 1 summarizes important developments since 2000. Since 2003, DPRK leadership transitioned from Kim Jong-il to his son, Kim Jong-un. The official nuclear status changed from the Agreed Framework's frozen nuclear program to a constitutional amendment that declares the DPRK as a nuclear weapon state.[5] The Yongbyon Nuclear Center evolved dramatically. First, the frozen plutonium production assets were put back into service, followed by the revelation of the addition of an experimental light-water reactor (LWR) program and an uranium enrichment program, in addition to a significant expansion of the fuel fabrication facility complex. The state declaration of nuclear weapon state status was preceded by three nuclear tests at the

[1] This research was supported by the Kyung-Hee Industry-Academic Cooperation Foundation, Republic of Korea. The objective was to assess the status of North Korea's Yongbyon Nuclear Center as of the date the draft report was submitted at the end of November 2015. In addition to the status of the facilities, we also provide a preliminary assessment of what would be required to decommission the facilities.

[2] North Korea told the U.S. delegation at trilateral (United States, North Korea, and China) talks in Beijing that it possesses nuclear weapons, according to Richard Boucher on April 28, 2003. (http://www.state.gov/dpbarchive/2003/20025.htm). This constitutes the first time that Pyongyang had made such an admission. https://www.armscontrol.org/factsheets/dprkchron.

[3] Officially known as the Yongbyon Nuclear Scientific Research Center.

[4] For detailed history of the end of the Agreed Framework and the Six-party process, see Mike Chinoy, *Meltdown: The Inside Story of the North Korean Nuclear Crisis* (2008); For broader history of the peninsula, including coverage of the nuclear program, see Don Oberdorfer and Robert Carlin, *The Two Koreas* (2014).

[5] North Korea Amends its Constitution", 2012. NK Briefs. The Institute for Far East Studies; North Korea proclaims itself a nuclear state in new constitution - CNN.com. Articles.cnn.com.

Punggye-ri test site and the construction of the new Sohae Satellite Launch site on the west coast. These changes will be recounted in the sections that follow.[6]

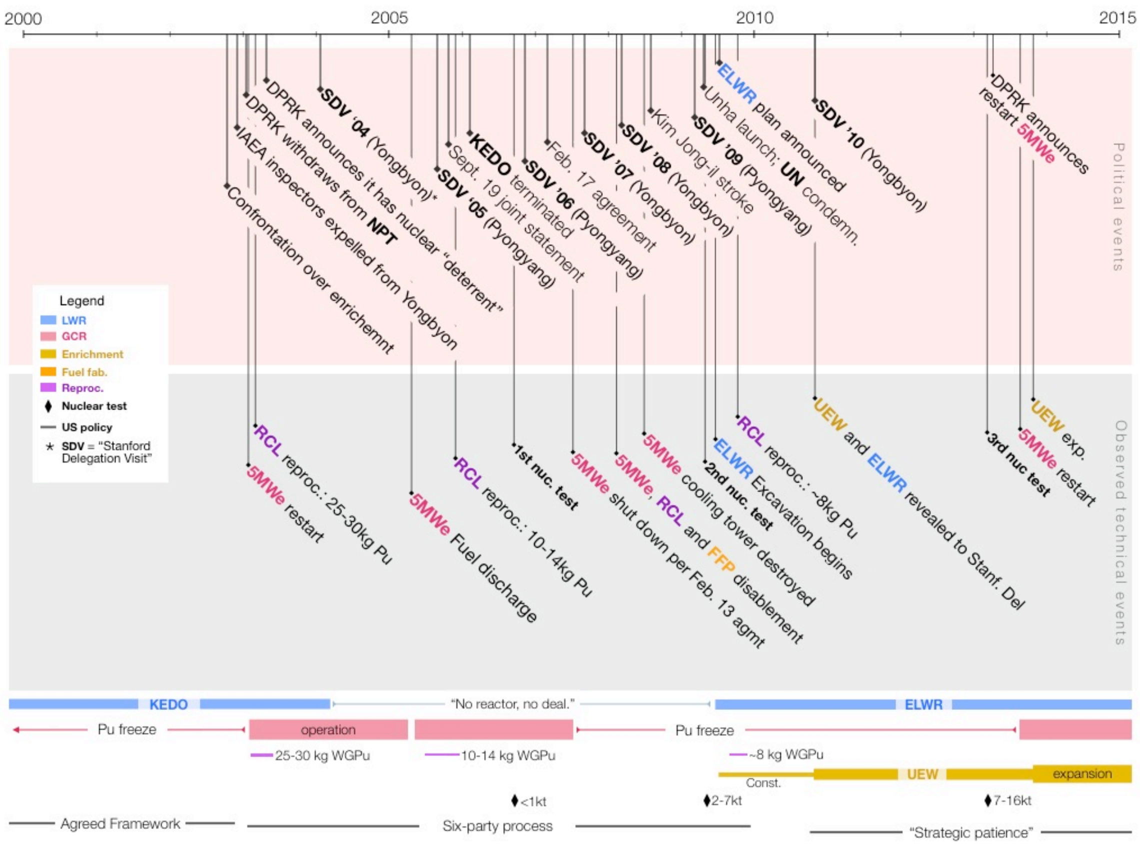

Fig. 1. Timeline of nuclear events since the collapse of the Agreed Framework (AF).

2. The 5MWe gas-graphite reactor

The 5MWe reactor at Yongbyon is a gas-cooled, graphite-moderated reactor (GCR) that uses MAGNOX fuel, which consists of natural-uranium alloyed with aluminum, clad in magnesium-aluminum alloy. The reactor is a smaller version of Britain's Calder Hall reactor[7], and it was originally intended as a pilot reactor in preparation for the larger 50MWe and 200MWe reactors that were partially constructed at the time the AF began (1994). Since MAGNOX fuel will corrode if stored in water, spent fuel from the 5MWe reactor cannot be stored indefinitely, and *must* eventually be reprocessed. The standard lifetime of a fuel core is three years, and in optimal operation, the 5MWe reactor is believed to be capable of producing 6 kg of plutonium (Pu) each year. The reactor typically operates for about three years then its entire core load is discharged and replaced with a new fresh uranium core. The discharged fuel is cooled in the spent fuel

[6] For technical details about events at Yongbyon prior to 2000, see David Albright and Kevin O'Neill, ed., *Solving the North Korean Nuclear Puzzle* (2000). See also, Jooho Whang and George T Baldwin, "Dismantlement and Radioactive Waste Management of DPRK Nuclear Facilities", Sandia National Laboratories Report SAND 2005-1981P, 2005.
[7] For information on the Calder Hall reactors, see "Calder Hall Power Station", The Engineer, 5 October 1956.

pool for several months and then it is sent to the radiochemical laboratory (described later) for reprocessing. A photo of the 5MWe reactor is shown in Fig. 2., and Fig. 3 shows an annotated aerial view of the reactor (along with the neighboring ELWR and spent-fuel storage building).

Most of what was known about the layout and technical characteristics of the reactor before the Agreed Framework is derived from the 1992 DPRK declaration to the IAEA and from the follow-on IAEA visit for verification.[8] The original thermal capacity was believed to be 20MWth, with an electrical output of 5MWe. The resulting thermal efficiency of 25% would be better than the 18% of the Calder Hall reactors. The reactor is equipped with at vertical charge-discharge machine for fuel insertion and removal, but unlike the Calder Hall reactors, it is believed that the reactor is usually shut down for fuel loading and removal. The reactor cooling system initially included a cooling tower, which was intentionally destroyed in June 2008. Subsequent cooling has included access and discharge to the Kuryong River (see Appendix. 1).

[8] Albright and O'Neill, 2000, Op. cit.

Fig. 2. 5MWe reactor at Yongbyon (S.S. Hecker).

Fig. 3. Physical layout of the 5MWe reactor at Yongbyon (image from Google Earth, 9/24/2014; CR 2015 DigitalGlobe).

2.1 5MWe reactor characteristics as described by Director Ri Hong Sop

The series of visits to the Yongbyon nuclear complex by the Stanford delegation provides one of the few direct sources of information about North Korea's nuclear program. This section provides details about the 5MWe reactor construction and operation as described to the Stanford delegations during these visits by Director Ri Hong Sop. Director Ri was very open and responsive to the myriad of questions asked by the Stanford delegation. His answers provided important information about current operation of the reactor and future prospects.

Director Ri explained that the 5MWe reactor was designed to be a prototype 25MWth carbon dioxide-cooled, graphite-moderated reactor. Design was completed indigenously by 1973. He stressed that they had no outside help, although the DPRK had good relations with the Soviet Union and China at the time. The reactor was constructed indigenously and became operational in 1986. This reactor was the prototype for larger power reactors designed for 50 MWe and 200 MWe. Director Ri said that they realize that these reactor designs are out of date.[9] Both of these reactors were under construction when the AF halted all work in Yongbyon in 1994.

The fuel rods loaded in January 2003 were fabricated before the AF. Yongbyon engineers had overcome initial reactor problems in which asymmetric neutron flux led to high temperatures in the lower portion of the core and frequent fuel-rod failure.[10] During early reactor operations in the 1980s, they had "flattened" the neutron flux by partial insertion of control rods. Later, selected fuel rods were replaced with steel dummy rods. The reactor's chief engineer indicated that these issues were taken into account in 2003 when the reactor was restarted. During the first year of operation after the restart, the reactor had experienced only one cladding rupture. The reactor was operating normally after January 2004, and Director Ri pointed out to the delegaton that a steam plume was emanating from the cooling tower as the members walked by.

In response to questions about the nature of the fuel and cladding, Director Ri said the magnesium alloy cladding was similar to the type used in the UK GCRs, which implies Mg-Al alloys (as opposed to Mg-Zr alloys used in French GCRs). When asked how long the fuel could reside in the reactor, he said that burnup levels of 1,000 to 3,000 MWth-d/ton can be reached with no problem (which is much longer than the 700 MWth-d/ton estimated for the 1994 campaign by Albright and O'Neill). According to Director Ri, spent MAGNOX fuel discharged after a burnup of 600 – 700 MWth-d/ton can be stored safely for up to five years before the cladding begins to corrode.[11] In general, Director Ri said that he considers the Pu from fuel exposed to burnup levels greater than 3,000 MWth-d/ton as unsuitable for nuclear weapons use due to higher production of even Pu isotopes. Hecker asked several times about the isotopic composition of the spent fuel that had recently been reprocessed, but Director Ri indicated that he was not authorized to share that information.[12]

During the visit to the reactor control room, it was evident that the reactor was operating at the time. The control room was quite old-fashioned, but looked functional (see Fig. 4). The dials showed it was operating at 100 % thermal power (25 MWth) and also that a 2.2 MW electrical generator was operating. Director Ri told the delegation that they had two steam turbines. The electricity produced was supplied to the local town, and hot water was provided for house heating (the dials indicated that the water temperature at the reactor exit was 76.7 C). The Stanford delegation was allowed to view the top of the reactor and the refueling machine. Director Ri said that it was possible to do on-line refueling, although that is not what they had practiced recently. However, in the 1986 to

[9] The French, for example, abandoned their version of gas-cooled reactors (UNGG (Uranium Naturel Graphite Gaz) for LWRs for power production. The French design was different than the British MAGNOX reactors design in that the steam generator was located directly above the reactor pressure vessel resulting in a very tall and very noisy reactor configuration. The DPRK realized that the predominant commercial reactor construction had gone to LWRs. They began discussion with Soviets in the 1970s and received a promise for VVER LWRs from the Soviets in 1984. However, the Soviets were not able to deliver on the agreement before the Soviet Union collapsed at the end of 1991.

[10] See Albright and O'Neill, 2000, Op. cit.

[11] This would require very precise control of the pH level of the water in the storage pool. When inspectors encountered the spent fuel in 1994 from the previous core discharge, Yongbyon scientists had not achieved this pH control, and some of the MAGNOX cladding had corroded. Thus, U.S. scientists had to re-can the spent fuel beginning in 1996 for storage during the AF.

[12] In subsequent discussions with Director Ri, it became apparent that the plutonium reprocessed at Yongbyon is weapons grade; that is > 93% Pu-239.

1994 period, they were able to refuel to replace damaged fuel rods while the reactor was operational.

The quick restart of the 5MWe reactor after having been shut down for eight years surprised many analysts. Director Ri told the delegation that they continued to do maintenance on the reactor during the AF. He also stated that they expect the reactor to remain functional indefinitely (implying several decades). No preservation work or maintenance was done on the 50MWe reactor and it looked in disrepair as the delegation drove by.

Fig. 4. Stanford delegation at the 5MWe reactor control room in January 2004 (S.S. Hecker).

Further information about the 5MWe reactor was provided by Director Ri during the August 2005 and November 2006 Stanford delegation visits to Pyongyang. The fresh fuel loaded in 2003 had been manufactured at least ten years earlier, so Yongbyon operators were not confident in the reliability of the cladding. For this reason, they opted to discharge the fuel at the end of March 2005 after only two years residence in core. However, Director Ri indicated that the fuel elements had held up well, with no corrosion of the MAGNOX cladding while in storage during the AF. A fresh fuel core was loaded and reactor operation was resumed in mid-June 2005, again at 25MWth. The spent fuel discharged in 2005 was reprocessed between June and December of 2005, likely yielding between 10-14 kg of WGPu (weapon-grade plutonium). Director Ri never shared the amount of Pu, nor its isotopic composition with the Stanford delegation.

During the November 2006 Stanford delegation visit to Pyongyang, Director Ri indicated that the reactor was operating but with some restrictions. Although the reactor was operating at its full 25 MWth, the output temperature had been reduced from 350°C to 300°C. He indicated that the lower temperature produces higher weapon-quality Pu, but it reduces the efficiency of the electrical power output. However, the principal reason for lowering the temperature was to avoid fuel-cladding failures. The reactor operators decide the operating temperature based on what is best for the safety of the fuel rods. Ri pointed out that replacing fuel rods is time consuming, so running at a lower temperature is advantageous.

The delegation asked if there had been many on-off cycles in reactor operations in the current campaign, as appeared to be the case from open-source overhead imagery. Director Ri claimed that there had not been, although they had removed damaged fuel rods a couple of times. They had inspected the fuel rods carefully before loading, and they examined them periodically while in the reactor. These were the only times reactor power had been lowered. “There have been no big fluctuations in power over the past year. We only did this during planned inspections.” He said that in 2005 they were concerned about the fuel rods, but that reprocessing campaign demonstrated that the fuel rods and cladding were generally in good shape. The fuel rods for the third campaign were also all fabricated before the 1994 shutdown prompted by the Agreed Framework. He was not particularly concerned about the current load of fuel rods because these were inspected before loading. Only a small number of rods had corroded,[13] and they found replacements for these rods. Overall, Director Ri was happy with reactor operations since the re-start in 2003. They only had to lower the temperature and do some minor maintenance and fuel rod replacements.

When asked about plans to unload the reactor, which had been operating with the current fuel load since June 2005, Director Ri said that technical considerations alone would dictate unloading some time in 2007. However, he pointed out other factors that he does not decide: “the political situation may change. So, sometimes we unload the reactor earlier even though it is less favorable for us technically.” When asked about the availability of another reactor core load of fuel rods, he said that at this point they still have a number of fuel rods from the pre-1994 inventory that was inspected by the IAEA. There were an insufficient number of fuel rods ready to load for a full reactor core of 8000 fuel rods. However, as noted below, they were able to use the fuel rods fabricated for the 50 MWe reactor to complete the next core loading in 2013.

Shortly after the 2006 Stanford delegation visit, on February 13, 2007, agreement was reached in Beijing during the fifth round (third session) of the six-party talks. This agreement called for an “action-for-action” process.[14] North Korea agreed to shut down the reactor, and carry out a series of “disablement measures” in parallel with resumed IAEA safeguards verification. After some delay (due to unexpected difficulty that Washington faced in unfreezing Banco Delta Asia funds as part of their end of the agreement)[15], the 5MWe reactor was finally shut down on July 15, 2007. The Stanford delegation visited Yongbyon in August 2007 and confirmed that the reactor and other facilities were no longer in operation. The delegation was also given unprecedented access to Yongbyon facilities, some of which had been off limits to IAEA inspectors. The

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[13] During a subsequent visit, Hecker was able to observe the fuel rods stored in a warehouse in the fuel fabrication facility since the Agreed Framework. Both the clad rods and the bare uranium metal rods were wrapped in clear plastic and appeared to be in good shape.

[14] See Chinoy, 2008, Op. cit.; see also Washington Post, http://www.washingtonpost.com/wpdyn/content/article/2007/02/13/AR2007021300508.html

[15] The U.S. Treasury Department sanctioned the Banco Delta Asia Bank and froze $25 million of DPRK assets in September 2005. See Chinoy, 2008. Op. cit.

delegation concluded that many of the facilities at Yongbyon were in poorer condition than they had expected, that initial steps toward disablement were being taken, but at the time these could be easily reversed. The 50MWe reactor looked in worse shape than during the 2006 visit. On the basis of discussions with Director Ri, the delegation concluded that it and the 200MWe reactor at Taechon were likely no longer salvageable.

A six-party agreement was reached on Oct. 3, 2007 on "disablement measures" to be carried out by December 2007, with supervision by a team of U.S. technical experts.[16] The Stanford delegation made independent assessment of the disablement progress during their February 2008 visit to Yongbyon. Of the 12 disablement measures, four were to occur at the 5MWe reactor:

- Secondary cooling loop outside reactor severed
- Cooling tower incapacitated (internal structure removed)
- Spent fuel being discharged (slowed to 30 rods/day to allow the other parties to catch up to the commitments they made)
- Control rod drive mechanisms to be removed – required until discharge complete.

Yongbyon officials went as far as to allow the Stanford delegation to take photographs of the disabled equipment. In his trip report, Hecker concluded: "Our visit leads me to conclude that the North Korean leadership has made the decision to permanently shut down Pu production if the United States and the other four parties live up to their Oct. 3, 2007 commitments. However, they had retained a hedge to be able to restart the facilities if the agreement falls through. We verified that the disablement actions taken to date would effectively delay a potential restart of Pu production. Cooperation between the U.S. and North Korean technical teams had been excellent, and until the recent slow-down, the two sides struck the proper balance between doing the job expeditiously and doing it safely. By their definition, North Korea had completed ten of twelve disablement actions. They had slowed down the last two to actions to allow the other parties to catch up."[17]

The most significant hurdle to restarting the reactor once the current fuel was fully discharged was to prepare a new load of 8,000 fuel rods. The Stanford delegation was shown the storage site for the fuel rods fabricated for the 5MWe and 50MWe prior to the Agreed Framework suspension. They were stored in a warehouse in plastic sleeves protecting the rods. Yongbyon officials indicated that they had roughly 1,700 clad fuel rods ready to load (not quite enough for one-fourth of a full core) and 12,000 bare fuel rods that were fabricated for the 50MWe reactor. These rods are approximately 10% longer than those used for the 5MWe reactor, but of the same diameter and composition. So, it appeared possible to stack these nine high in the reactor instead of ten high as is done with the 5MWe rods. Consequently, DPRK would be able to produce one more load of 8,000 rods by using a combination of rods fabricated for the two reactors. However, the 50MWe rods would have to be clad with Mg-Al alloy cladding. Reconstituting the cladding operations or, if needed, machining operations was made more difficult by the disablement actions at the fuel rod metal fabrication facility (see Sec. 6).

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[16] Lewis, Jeffrey. 2010. "The Cooling Tower." 38North.org. October 15. See also: Hecker, Siegfried. 2008. "Report of Visit to the Democratic People's Republic of North Korea (DPRK). Pyongyang and the Nuclear Center at Yongbyon, Feb. 12 - 16, 2008." Center for International Security and Cooperation.
[17] Hecker 2008, Op. cit.

A number of proposals were made to strengthen the disablement actions. One of these was to have the DPRK consider selling the stored fuel rods, which contained roughly 100 tons of uranium. An offer was made by South Korea during a visit to Pyongyang in January 2009 by Hwang Joon-kook, Director-General, North Korean Nuclear Affairs Bureau and Ambassador for North Korean Nuclear Issue, Ministry of Foreign Affairs and Trade. No deal was consummated because apparently the DPRK asked for an exorbitant fee.[18]

On June 27, 2008, North Korea collapsed the cooling tower of the 5MWe reactor with a controlled explosion as a good-will gesture, allegedly in return for a $2.5 million payment from Washington. In addition, Pyongyang delivered a declaration of nuclear facilities to China, the host of the ongoing six-party talks. Pyongyang had previously provided Washington with copies of 18,000 pages of operating records for the reactor and the reprocessing facility. The declaration included the claim that North Korea had an inventory of 30 kg of Pu. It also claimed that only 2 kg of Pu were used in the May 2009 nuclear test, a claim we consider not credible.

During the rest of 2008, there continued to be diplomatic disagreements about the pace of reactor core unloading, the completeness of North Korea's nuclear declarations and the pace at which Washington and its partners were delivering the heavy fuel oil promised as part of the 2007 agreement. In early August 2008, Kim Jong-il suffered a serious stroke, which undoubtedly caused a scramble for influence and lines of succession in Pyongyang. In spite of repeated attempts by Assistant Secretary Chirstopher Hill to seal a deal during the last few months of the Bush administration, nothing was accomplished before President Obama took office in January 2009.

During the February 2009 visit to Pyongyang, the Stanford delegation was told that the DPRK planned another long-range rocket launch. When the delegation expressed its dismay that this was no way to greet a new U.S. administration, the North Korean hosts said the decision was irreversible. They also claimed that it was partially in response to the parties in the six-party talks not having fulfilled all their obligations in the 2007 agreements. Following the April 2009 launch of North Korea's second Unha-2 rocket test, the UN Security Council issued a statement condemning the launch. In response, the DPRK rescinded the February 13, 2007 accord, ejected IAEA inspectors from Yongbyon, and announced its intention to reprocess the spent fuel from the reactor core. On May 25, 2009, Pyongyang conducted its second nuclear test and on Nov. 3, 2009, KCNA announced that reprocessing of the spent fuel unloaded earlier in the year had been completed. The reactor appeared to be left dormant during the rest of 2009 and 2010.

The Stanford team requested visits to Yongbyon in early 2010, but were told several times that the time was not yet right. In August the team got word that they were welcome to return later in the fall. The visit took place in early November 2010. The timing appeared to be closely coordinated with the completion of a new Yongbyon facility. During the Pyongyang part of that visit, the Stanford delegation was told by Vice Minister Ri Yong-ho that the DPRK would convert the Yongbyon Nuclear Center to an LWR and pilot enrichment facility. As discussed in Sections 4 and 5, the delegation was shown the beginning of construction of the new ELWR and a modern centrifuge facility during the visit. Vice Minister Ri told the delegation, "no one believed us when we

[18] Arms Control Association, https://www.armscontrol.org/factsheets/dprkchron

announced this in 2009, including you Dr. Hecker."[19] This visit appeared to indicate that North Korea had, indeed, decided to convert the Yongbyon Center from Pu production to build an LWR and uranium enrichment. During the 2010 visit to the ELWR construction site, which is close to the 5MWe reactor site, Hecker asked the chief engineer about the status of the reactor. He said they had it in stand-by condition at the time. When Hecker said that many people in the West believe that it is no longer operable, the chief engineer smiled and said "that's what they said in 2003 when we restarted the reactor after the Agreed Framework." In April 2013, Pyongyang announced plans to restart the 5MWe reactor, and first indications of reactor operation were visible from satellite imagery in August 2013. It is not clear what caused the 2009 to 2013 delay, though this was possibly because of a lack of an adequate reactor cooling option. The completion of the pump-house for the ELWR in 2013 created a new cooling option for the 5 MWe reactor and allowed its restart, as discussed in Appendix 1 below. Intermittent, low-power operation has been observed since, including a likely shutdown for part of 2014. Albright and Kelleher-Vergantini report that North Korea apparently completed retrofits and upgrades of the reactor in that time frame.[20]

Albright and Kelleher-Vergantini also report that North Korea reportedly installed or (renovated) irradiation channels in the core and go on to speculate that one of the isotopes that may have been produced in the reactor is tritium. Tritium production could also have been achieved by using one of the fuel channels to irradiate Li-6 targets. Tritium together with deuterium can be used to boost the yield of a fission weapon (for purposes of using less fissile material and miniaturization) or in the design of a fusion, that is, thermonuclear weapon. Tritium production in North Korea has never been confirmed. However, on May 12, 2010, the official Korean Central News Agency said: "The successful nuclear fusion by our scientists has made a definite breakthrough towards the development of new energy and opened up a new phase in the nation's development of the latest science and technology."[21] This announcement was believed to refer to achieving fusion for civilian application, which is much more difficult than fusion driven by a fission bomb. Nevertheless, the possibility of tritium production in the 5 MWe reactor could explain why the reactor remains operational in light of the apparent buildup of uranium enrichment capabilities. A more detailed discussion of the possibility of tritium production in Yongbyon is available in Appendix 3 below.

2.2 Future prospects for the 5MWe reactor

Indications are that the 5MWe reactor may continue functioning for several more years, even in its old and dilapidated state. This is subject to adequate supply of fresh fuel to prepare a new core load once every two or three years. While North Korea now has

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[19] In a September 4, 2009 letter to the President of the UN Security Council, the North Korean permanent representative to the United Nations stated that North Korea's "experimental uranium enrichment has successfully been conducted to enter into completion phase." (Korean Central News Agency – KCNA). This announcement followed Pyongyang's earlier announcement that it will develop its own LWR reactor.
[20] David Albright and Serena Kelleher-Vergantini, "Update on North Korea's Yongbyon Nuclear Site," Institute for Science and International Security Imagery Brief, September 15, 2015. http://isis-online.org/isis-reports/category/korean-peninsula/#2015
[21] Justin McCurry, The Guardian, "North Korea claims nuclear fusion breakthrough," May 12, 2010. http://www.theguardian.com/world/2010/may/12/north-korea-creates-nuclear-fusion-claim

other uranium requirements associated with its nascent LWR program, there is an abundance of known uranium reserves in the country. The pacing item will be the need to revitalize the entire metal fuel rod fabrication capabilities, many of which were moved from the buildings during the 2007-2008 disablement operations. This will require significant effort, but can be accomplished without extreme difficulty. The main issues will be political and economic, rather than technical. The 5MWe reactor is the only source of Pu, which has been depleted by the conduct of several nuclear tests. The continuing delay in the start-up of the ELWR may also make it more attractive to keep the 5MWe reactor in operation.

Another constraint on the operation of the 5MWe reactor is the availability of adequate cooling water from the Kuryong River (see Appendix 1). It is also possible that some of the old equipment in the reactor -- a gas circulator (the blower) or the steam generator, for example, may fail and the cost of replacing the radioactive component with new equipment may not be worth the trouble. The control system of the reactor is also aging and some of its components may fail as well, though these are more easily replaced. Whether or not to continue to operate the 5MWe reactor will likely be a political rather than technical decision. It is possible that Pyongyang has made the decision to focus its nuclear weapons program on highly enriched uranium (HEU) rather than Pu. The HEU route has much greater prospects for scale-up than the Pu route. The best the 5MWe reactor can do is to produce approximately 6 kg of Pu (one bomb's worth) per year under ideal conditions. However, it is likely that North Korea's nuclear test experience is either wholly or primarily based on Pu devices, so the Pu route will likely not be jettisoned altogether.

If a decision is made to unload the core in the reactor at the end of 2015, the spent-fuel rods will likely be reprocessed in the radiochemical laboratory (RCL). At that time, the fuel load is believed to contain less than 6 kg of Pu because of the intermittent operation of the reactor. If a political denuclearization agreement is eventually reached, it is imperative that the 5MWe reactor is permanently disabled and dismantled. Several previous agreements to halt operations were all subsequently reversed. We believe that this may likely be the case again in the future. Since the primary purpose of the reactor is Pu production (with the possibility of additional tritium production as mentioned above) and since Pu is used for bomb fuel, the 5MWe reactor must be taken out of service in any future denuclearization agreement.

If a political decision is made before the current reactor core is unloaded and reprocessed, then the parties to the agreement must make a difficult choice as to what to do with the spent fuel. In 1994, the decision was made to leave the fuel in the cooling pool. However, that turned out to be problematic because the spent fuel rods were corroding in the pool. It took the American technical team many years and millions of dollars to re-can the fuel. The AF did not settle the issue of the permanent disposition of the spent fuel. The expectation was that it would be removed from North Korea and reprocessed in another country.[22] However, in 1994 the re-canned fuel was left in the

[22] It was not surprising that the DPRK wanted to keep the spent fuel at least until the United States made substantial progress with the LWR construction. As for eventual disposition of the spent fuel, the UK and France both had the requisite reprocessing capabilities, but the political issues would have to be addressed to allow such transport and reprocessing.

pool, only to be reprocessed in 2003 by North Korea once the Agreed Framework was terminated to extract Pu bomb fuel.

From a technical standpoint, it is advisable to allow Pyongyang to reprocess whatever spent fuel is in place at the time of a future agreement. It is considerably easier to safeguard and ship a few kilograms of Pu than it is to ship 50 tons of spent fuel that is highly radioactive. Furthermore, only few facilities worldwide could still accept such MAGNOX spent fuel for reprocessing and the cost of reprocessing in a Western country would far exceed the cost of such an operation being carried out in North Korea. In any case, once the fuel is removed from the reactor, it will be possible to start dismantling facilities on site. The turbine hall and other non-nuclear structures in the 5MWe reactor complex could be decommissioned and dismantled first. Eventually, only the reactor building and the spent-fuel storage building will remain. Those facilities could be shuttered (all useful equipment being removed) until a decision is reached on how to decommission the nuclear part of reactor. In general, it is likely to take one to five years to permanently shut down the nuclear facilities in Yongbyon, depending on the disposition of the spent fuel. Full dismantlement and cleanup will require more than ten years, and can be carried out by the Yongbyon nuclear staff. Experience in decommissioning MAGNOX reactors in the UK would be of value at that point.

3. 50MWe and 200MWe gas-graphite reactors

As mentioned above, the 5MWe reactor was built as a prototype for two larger reactors that the Stanford delegation was told in 2004 were to be commercial power reactors. Director Ri said that the 50MWe reactor was within one year of completion at Yongbyon and the 200MWe reactor had been under construction for two years some 20 km away at Taechon.

In Jan. 2004, the Stanford delegation drove by the 50 MWe reactor. The outside of the reactor building looked in bad repair. Apparently, the construction cranes were removed and nothing else had been done to the site during the AF freeze. Two large cooling towers originally planned for the operation of the 50 MWe reactor had never been completed. Satellite imagery showed that only a part of the concrete foundation had been put in place. In August 2005, Director Ri told the Stanford delegation that they had completed a design study that concluded that construction of the reactor could continue on its original site with much of its original equipment. They are able to keep the original structure and containment shell. He said that the core of the reactor and other components were already fabricated, but were not at the Yongbyon site. He said the Yongbyon workers were ready to resume reactor construction, although he did not give an expected completion date. He expected they would be able to complete the reactor soon, but did not indicate how soon. The implication was a couple of years, rather than five or six.

During the 2006 visit, the Stanford delegation was told that virtually nothing had been done at the 50 MWe reactor site and that they have run into some difficulties. Director Ri said they were in a partial preparation, not in full swing. He said the effort was directed at recovering the original state of the equipment; for example, removing rust from the steel. He told the delegation that the main problem was the preparation by other industries, recovery in other factories, not on site at Yongbyon. Responding to the question about having all materials for this construction job available within North Korea, he answered, "It is difficult to import (anything), so we must do everything ourselves. It will take longer." When asked about the timing of resuming full operations, he said, "I have sent a schedule to the higher level, but have not yet received instructions. I expect to get instructions soon."

Nothing had been done at the 200 MWe construction site at Taechon since the Agreed Framework freeze was instituted in 1994. Director Ri told the delegation in 2005 that they are still studying what to do with the reactor. He said it is most likely less expensive to start over than to continue on the current site. During the 2006 visit, he told us that there is nothing new on this reactor. He said: "We will sequence the decision. First, we will do the 50MWe reactor, then we'll address the 200MWe reactor."

It is possible that either technical or financial difficulties had slowed down the resumption of full-scale construction of the 50MWe reactor. Although, a political decision on a full restart apparently had not yet been made by 2006, these difficulties put the completion of the reactor and a significant scale-up of Pu production at least several years into the future. In 2007, the February 13 agreement appeared to settle the question of the two reactors – the political decision finally came in line with the technical issues on the ground; that is, the freeze during the Agreed Framework made these reactors not worth salvaging. During the November 2010 visit to Yongbyon, the Stanford delegation saw that the 50MWe reactor was being torn down.

Since nothing has been done since that time to rebuild the larger reactors, it appears that the decision to build LWRs starting with the small experimental prototype ELWR ends North Korea's experiment of trying to build a domestic version of commercial GCR reactors. We caution, however, that it is conceivable that under some circumstances Pyongyang may decide to revive this path for Pu production. They clearly have the know-how and likely all the materiel required to pursue the construction of a new 50MWe. By doing so, Pyongyang could increase its Pu production to roughly 10 bomb's worth per year – a troublesome possibility.

3. IRT-2000 research reactor

The IRT-2000 is a Soviet Union-supplied 'pool-type' research reactor, which is fueled by enriched uranium and moderated and cooled by light water. Construction occurred over the period from 1963-1965. In its original configuration, the reactor used uranium fuel (EK-10) enriched to 10% (U-235) and operated at 2MWth. North Korea independently upgraded the IRT-2000 three times: in 1974, the fuel enrichment was changed to 80%, and the power was increased to 4MWth; in 1984, fuel enrichment was changed to 36% (IRT-2M fuel); in 1987 the power was upgraded to 8MWth, and the core was redesigned to incorporate a mixture of fuel enriched to levels of 10%, 36% and 80%. This composite core is the reactor's current configuration.[23] All enriched uranium fuel was supplied by the Soviet Union until the end of the Cold War. Research reactors have several functions, including (but not limited to) radioisotope production, investigation of physical and chemical processes under irradiation, support of power-reactor programs,

[23] Ira N. Goldman, et al., "Possible Cooperative Projects for Utilization of the DPRK's IRT-2000 Research Reactor", http://sites.nationalacademies.org/cs/groups/pgasite/documents/webpage/pga_057020.pdf; See also: James Clay Moltz and Alexandre Y. Mansourov, eds. *North Korean Nuclear Program: Security, Strategy and New Perspectives from Russia*, 2000, Routledge, New York and London.

and education. But now that no fresh fuel is available the reactor can only be operated sparingly, and primarily for radioisotope production.

Alongside the IRT-2000 reactor, the Soviets built a small isotope-production laboratory (IPL) that consisted of twenty glove boxes and twenty hot cells. This laboratory made it possible to extract radionuclides (with activity equivalent to 5 kg of radium) from irradiated fuel assemblies. The possible use of these facilities for tritium production is discussed in Appendix 3.

Although the Stanford delegation was not allowed to visit the IRT-2000 reactor, conversations with Director Ri during several of the visits provide useful information about the status and future prospects of the reactor. Director Ri indicated that there is an urgent need for medical isotopes in North Korea, particularly ^{131}I, and the reactor is intermittently run in order to produce these. Ri told the delegation that the most recent fuel supplied by the Soviets was in the 1980s, and that the 80% enriched fuel is in particular short supply. Director Ri also pointed out that the only other domestic source for short-lived isotopes is a cyclotron in Pyongyang.

During the August 2008 visit to Yongbon, Hecker and Director Ri further discussed potential future uses for the IRT-2000 reactor. They developed a list that included:

- radioisotope production (primarily for medical applications)
- neutron-activation analysis
- neutron diffraction and radiography
- neutron-transmutation doping
- reactor fuel studies
- neutron radiation cancer therapy.

Yonbyon officials responded that they have experience with some of the applications mentioned. Since fuel supply is the main barrier to future operation of the reactor (Hecker pointed out that it would not be possible to supply HEU fuel because of the proliferation risk), Director Ri indicated that it would be possible to convert the core back to its original configuration using low-enriched uranium (LEU) fuel. When asked how long Yongbyon engineers expected to run the reactor (if provided with fuel), Ri replied that the only problem with the reactor itself had been with the reactor lining. If the lining were to be changed, Ri predicted that the reactor could run for another 20-30 years.

Yonbyon officials also stated that they have experience in the production of medical and industrial isotopes. The IPL has channels that allow them to reprocess targets and extract the radioisotopes of interest. Director Ri said that they have not performed irradiation cancer treatments. Director Ri expressed interest in exchange in this area because cases of thyroid cancer in the Yongbyon area have gone without treatment due to lack of radioisotopes. We note that North Korea had also developed the capability to separate isotopes in nearby Isotope Production Laboratory. In light of potential tritium production discussed above, this laboratory also could have been used for separating tritium.

During the discussions about the future of the IRT reactor, Director Ri also expressed concern to the Stanford delegation that if Yongbyon were to shut down, he and his colleagues would need to find new employment. For this reason, he would like to put their technical people into projects for LWRs in order to retrain them.

4. Light-water reactors

Alongside the GCR complex, North Korea has had a sustained interest in LWR technology, and this interest appears to have survived the end of the AF and associated Korea Energy Development Organization (KEDO) project. The desire to obtain LWRs through international agreements played a central role in the six-party negotiations. But in 2009, Pyongyang decided to embark on an indigenous LWR program, and began construction of the Experimental Light Water Reactor (ELWR) at Yongbyon. This section presents information from the Stanford delegation visits that may shed light on North Korea's decision-making process along the way, and then summarizes what we know about the ELWR from discussion with Director Ri and from satellite imagery.

4.1 North Korea's evolving strategy for obtaining LWR technology

North Korea's desire to obtain LWR technology has survived the demise of the AF, and persists to the present day. During the first Stanford delegation visit in 2004, Director Ri emphasized that LWR technology was superior to GCR technology for electricity generation, and that MAGNOX reactors were considered obsolete.[24] The LWRs, of course, played a central role in the Agreed Framework. KEDO was established to build two modern 1,000 MWe LWRs in return for Pyongyang freezing its Yongbyon nuclear program. It was a swap that North Korea welcomed, especially since it also included provisions of heavy fuel oil and the promise of diplomatic normalization.

The Agreed Framework came to an end shortly after the U.S. – DPRK altercation over an alleged uranium enrichment program in October 2002. This halted progress on the KEDO project, although KEDO's official demise did not occur until May 31, 2006. DPRK officials resurrected its request for LWRs during the fourth round of the six-party talk in July 2005 at a time when diplomatic progress was being made toward a return to a nuclear agreement. However, the request for an LWR was rejected by Washington, which first called for complete, verifiable, irreversible dismantlement CVID) of North Korea's nuclear program.

During the second Stanford delegation visit in 2005, Hecker attempted to persuade Vice Minister Kim Kye-gwan (who was also the chief negotiator for the North in the six-party talks) that fossil fuel plants or electrical transmission from Russia or South Korea were significantly better and faster options for the North to build electrical generation capacity. Vice Minister made it clear that the North wanted nuclear energy, and that it had symbolic as well as practical value to them. In the end, he told the delegation "no LWR, no deal".

There was also discussion between Hecker and Director Ri about the comparative risks and benefits of LWRs and GCRs. Director Ri said that LWR fuel is not suitable for nuclear weapons at normal burnup levels. He also indicated that he does not consider spent GCR fuel at burnup levels exceeding 3,000 MWth-d/ton to be a proliferation risk.

[24] The last MAGNOX reactor to be built outside of North Korea was finished in 1971. See http://www.neimagazine.com/features/featureinter-reactor-fuel-transfer-at-wylfa-12-4275091/.

Both Director Ri and Vice Minister Kim indicated that proliferation risks of LWRs can be managed by establishing fuel supply and spent fuel recovery agreements internationally. However, at that time, Director Ri still favored GCRs over LWRs for the North Korea.

Hecker and Professor Lewis relayed North Korea's insistence on obtaining LWRs to Secretary of State Condoleezza Rice in early September. This may have contributed to a softening of the U.S. position on the provision of LWRs, the six parties subsequently signed the September 19, 2005 Joint Statement to denuclearize the Korean Peninsula. However, problems with the diplomatic process persisted.

During the August 2007 visit of the Stanford delegation, Vice Minister Kim discussed the issues of disablement as agreed to in the February 13 joint statement. He reiterated that the agreement was for initial disablement, not for irreversible disablement (meaning dismantlement). Vice Minister Kim continued to stress the importance of obtaining LWRs during several meetings with the Stanford delegation in 2007. He explained that North Korea is committed to giving up the GCRs, but that nuclear energy is their policy. It would be easier to justify abandoning the GCRs to their people if they had an assurance that they would receive an LWR. When the topic of proliferation risks resurfaced, Kim said that he understands that even with the LWR there are ways to produce nuclear weapons. He said that the best way to verify and monitor a North Korean reactor is to jointly operate it. Kim then added that if the United States did not help North Korea obtain LWRs, then "we will go our own way. And if we do so, we will need to do enrichment ourselves." To our knowledge, this was the first time that North Korean officials hinted at building their own LWR and having to develop indigenous enrichment capabilities.

Although North Korea and the United States worked quite well together during the remainder of 2007 and into 2008, no progress was made regarding the LWR issue. In February 2008, during discussions about potential redirection of the Yongbyon workforce, Director Ri Hong-sop indicated to Hecker that in the future they would like the Yongbyon workforce to be directed to peaceful nuclear energy. He implied that if an LWR were introduced, Yongbyon technicians and engineers would be trained for the LWR. They were also considering how to train their nuclear engineers in other areas. During prior visits, Director Ri had indicated that his people had not been involved in the KEDO LWR project.

The Stanford delegation visited Pyongyang in late February 2009, expecting a warm reception because of the change of U.S. administration to President Obama. Instead, it was warned that things would get worse, beginning with a planned rocket launch in the near future. It was surprising that the cooperation in 2007 and 2008 had come to an end. The purported reason was the fact that the United States and its partners were not living up to their October 3, 2007 agreement commitments, but we may never know the real reasons[25]. However, our host Ambassador Ri Gun also foreshadowed a decision to have Pyongyang develop its own LWR. He indicated that the U.S. actions left them no choice but to develop their own LWR.

[25] We note that a number of potential drivers may have moved the DPRK in this direction. First, Kim Jong-il suffered a debilitating stroke in August 2008 and must have been concerned about succession. In February 2008, Lee Myung-bak was elected to the presidency of South Korea. By the fall of 2008, it was clear that the previous sunshine policies toward North Korea were terminated since President Lee took a much harder stance toward the DPRK. Finally, it is our technical judgment that the DPRK had to do another nuclear test since the first one clearly did not work so well.

Following North Korea's April 5, 2009 rocket launch (which failed, but was claimed by KCNA to have been a successful satellite launch), the United Nations Security Council (UNSC) condemned the launch and its violation of UNSC resolutions. The DPRK denounced and rejected the UNSC statement, expelled the international inspectors and the U.S. technical team from its Yongbyon complex, and threatened to strengthen its "self-defensive nuclear deterrent." It also announced that it would resume normal operations at Yongbyon and reprocess the spent fuel that had been in the cooling pool since 2007. On April 29 it followed with a statement threatening a nuclear test and to "make a decision to build a LWR power plant and start the technological development of ensuring self-production of nuclear fuel as its first process without delay" unless the UNSC promptly apologized for its infringement on North Korea's sovereignty.[26]

In retrospect, these were clear signals by the DPRK that it had abandoned diplomacy with the six-party process and decided to build its own LWR and enrichment capability. On May 25, the DPRK conducted its third nuclear test, this one apparently quite successful. In response to North Korea's May 25 nuclear test, the UN Security Council unanimously adopted Resolution 1874, which expanded sanctions against Pyongyang. In a September 3, 2009 letter to the UN Security Council, North Korea announced, "Experimental uranium enrichment has successfully been conducted and entered into the completion phase."[27] Most U.S. analysts, including Hecker, did not take these pronouncements very seriously. The Stanford team sent requests to Pyongyang several times in 2010 to observe what changes were being instituted at Yongbyon in 2010. The Stanford delegation was finally allowed to visit Yongbyon in November 2010. It was not until they saw the start of construction of the ELWR and the completed, modern centrifuge facility that they understood North Korea's determination to pursue and indigenous LWR program.

4.2 The Experimental Light-water Reactor (ELWR)

Based on the information presented above, we conclude that North Korea likely made the decision to build its own LWR some time in the latter half of 2008. The decision to build an enrichment facility and freeze the design of the centrifuges was probably also made at that time as seen from the centrifuges construction schedule proposed in Appendix 2. During the 2010 visit to Yongbyon, the Stanford delegation was shown the foundation of the new ELWR in an early stage of construction. At the new three-story Guest House at the Yongbyon Nuclear Center, we were given the following introduction: "In the 1980s and 1990s, we agreed to give up our reactors for LWRs, 2,000 Megawatt-electric (MWe) by 2003. In the early 1990s we built 50 and 200 MWe reactors (of gas-graphite design). Now they have become ruined concrete structures and iron scrap. We have not been able to contribute to the national demand for electricity. So, we decided to make a new start. For us to survive, we decided to build our own LWR."

On April 15, 2009, the Foreign Ministry announced, "We will proceed with our own LWR fuel cycle. We have completed the discharge of the 5MWe spent fuel, reprocessed it and delivered it to the military for weaponization. Our nuclear program has not proceeded as expected, we have not delivered electricity and that has impacted the

[26] Oberdorfer and Carlin, Op. cit.
[27] North Korea Nuclear Chronology, Nuclear Threat Initiative. *www.nti.org/media/pdfs/north_korea_nuclear.pdf?*

economic condition of our country. We will use our economic resources to solve the electricity problem. We are willing to proceed with the six-party talks and the September 19, 2005 agreement, but we cannot wait for a positive agreement. We are trying our best to solve our own problems. We will convert our center to an LWR and pilot enrichment facility. It is a high priority to develop uranium enrichment. We will have some difficulties with this, but we are proceeding with the LWR fuel cycle. We have designated a site for the LWR and also for uranium enrichment – it is the first stage, so it is first priority. The construction is completed and the facility is operational. You will be the first to see this facility."[28]

The delegation was escorted to the ELWR site by Chief Engineer Yu, who was also the former chief engineer for the 5MWe reactor. Yu was also slated to take charge of the ELWR once it was completed. At the site there was a large excavated pit roughly 40 meters by 50 meters by 7 meters deep. A concrete foundation 28 meters square with round concrete preforms for the reactor containment vessel was visible. The containment vessel was about one meter high at the time. The delegation was told the vessel would be 22 meters diameter, 0.9 meters thick and 40 meters high. It is designed for a power level of 100 MWth. Yu chose not to specify the electrical power, but said that the conversion efficiency is typically 30 percent. Therefore, Hecker estimated the electrical power to be roughly 25 to 30 MWe.

Chief Engineer Yu explained that LWR design is different from their experience base associated with GCRs; hence they are building this small prototype first. Once they master this technology, they would build a larger LWR suitable for significant energy generation. However, even with the 25 to 30 MWe reactor, they planned to build two electrical generators that will supply electricity to the local communities and be connected to the national grid. Yu said the construction was started on July 31, 2010, and that the target date for operations is 2012 (which is unreasonably optimistic, but coincides with the centenary of Kim Il-sung's birth and is the target date for most current major projects). There were nearly 50 workers on the floor – all of them dressed in dark blue coveralls and wearing hard hats. Hecker asked about reactor safety analysis and practices. They claimed to have excavated down to the bedrock and that they had performed seismic analysis of the site. However, the construction site showed little evidence of deep excavation.

The pressure vessel was said to be fabricated out of high-strength steel, possibly with a stainless-steel liner. Yu said that they would be able to manufacture it domestically. They will produce all the pumps and other reactor components domestically and have the requisite welding capabilities. In addition to the usual propaganda signs, they displayed the following safety sign at the site: "Safety first – not one accident can occur!" Hecker asked if they have a nuclear regulatory agency. Yu said that the National Nuclear Safety Commission has oversight. They submitted their plans to the Commission, which inspects the site. They have nuclear specialists on the Standing Committee and have inspectors on the site.

The reactor will be fueled with uranium dioxide (UO_2) fuel enriched to ~3.5%, typical for LWR fuel, but very different from the metallic uranium alloy fuel rods used in

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[28] 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.*

the GCR. A full load of fuel is comprised of four tons of uranium. In a separate discussion, they reiterated that they had ample domestic uranium ore resources. They were not certain what cladding material would be used, stating that they are still working on many of the details. The reactor design team is a new, young team without reactor design experience. However, Yu assured the Stanford delegation that they would be mentored by the experienced GCR designers. The new designers are in their 40s, graduated from North Korean universities and have spent their careers at Yongbyon. They have not brought any of the North Korean KEDO LWR team members to Yongbyon at this time, but may do so for the operational phase.

Hecker and his colleagues left the construction site with serious concerns about the ability of North Korea to operate the ELWR safely once it is complete. The construction that was visible did not come close to reactor-grade concrete work for the containment structure. There appeared to be little hope of having an independent nuclear regulatory authority oversee the construction process. In addition, the young, inexperienced team that designed the reactor was cut off from the global community of LWR expertise.

Table 1 summarizes our estimates of the basic design characteristics, along with observations and/or reasoning leading to our estimates. Many details, such as fuel cladding and pressure-vessel dimensions, were either unknown to Yu at the time of the visit, or simply withheld. Some of these aspects can be surmised based on standard practices related to pressurized LWR technology established elsewhere, or on other information about North Korean capabilities. For instance, while it was not known if the cladding material would be zircaloy or stainless steel, it is more likely that stainless steel will be employed because there is no known zirconium production within North Korea. Since steel absorbs more neutrons than zircaloy, a somewhat higher fuel enrichment level would be required. Other properties will depend on the annual capacity factor that the ELWR is designed to achieve once operation commences. In the table, estimates that are not based on explicit indication by Chief Engineer Yu are listed in italics. Since North Korea has not yet published any design information on the reactor, the data presented in Table 1 should be considered preliminary.

Table 1. Estimated properties of the experimental light-water reactor (ELWR).

Property	*Estimate*	*Data/reasoning*
Reactor type	Pressurized water reactor (PWR)	Chief Engineer Yu indication to Hecker during 2010 visit to Yongbyon
Thermal power	100 MWth	Chief Eng. Yu ind. 2010
Electrical generation power	25 - 30 MWe	Chief Eng. Yu did not specifically state the power, but pointed out that it is typically 30% of thermal power
Fuel type	UO_2	Chief Eng. Yu ind. 2010
Fuel-load size	4 tons UO_2	Chief Eng. Yu ind. 2010
Average enrichment level	3.5% ($^{235}U/^{tot}U$)	Chief Eng. Yu ind. 2010
Cladding	*Unknown; likely stainless steel*	Chief Eng. Yu ind. 2010; likely availability of material

Containment structure dimensions	*Dia.* = 22 meters *Ht.* = 40 m *Thickness* = 0.9 m	Chief Eng. Yu ind. 2010; confirmed by satellite imagery
Excavation depth	7.1 m	Chief Eng. Yu ind. 2010; confirmed by satellite imagery
Concrete foundation dimensions	28 m	Chief Eng. Yu ind. 2010; confirmed by satellite imagery
Pressure-vessel material	High-strength steel; possibly stainless-steel liner	Chief Eng. Yu ind. 2010
Average burnup	*~33,000 MWth-d/ton*	This is standard for PWRs; no specific information available on burnup for ELWR
Secondary cooling	Water from Kuryong river	Pump house, intake piping and cisterns, and discharge piping identified via satellite imagery
Fuel-building location	*East-facing side of bldg. between reactor and turbine halls*	Distinguishing features visible: - extends above roof to allow crane movement; - partitioned into fresh and spent fuel rooms
Spent fuel (U / year)	*~1 ton / year*	Truck entrance for fuel delivery visible;
Electrical turbines	2 in parallel	Chief Eng. Yu ind. 2010

The basic features of the facility's physical layout are visible from satellite imagery. Figure 5 shows an overhead image of the facility after completion of the civil-engineering phase. The nuclear building, which includes the cylindrical reactor containment structure surrounded by a square "wrap-around" service building and topped by a dome, is located on the north (right in the figure) side of the facility. The turbine hall is located just south (left) of the nuclear building.

There is a long connecting section between the two halls that runs the east-west width of the facility, connecting the front (west) and rear (east) entrances. We assess that the reactor control room is located at the front end of this connecting section, and takes up floors above the front entrance. This would be similar to the control-room location of the Uranium Enrichment Workshop (UEW) as observed by the Stanford delegation in 2010.[29] The fuel building appears to be at the rear of the connecting section, directly above the rear entrance and extending above the roof of the section. This allows room for crane operation above, and for delivery of fresh fuel through the rear entrance. Earlier images taken in March 2013 indicate that the fuel building is partitioned, consistent with separation of fresh- and spent- fuel rooms.

The electrical building and substation – expected for extracting and contributing (respectively) electricity to the national electrical grid – are not visible in the image.

[29] Hecker, 2010, Op. cit.

Since the reactor is small, it may be that some of the electricity supply equipment is included inside the turbine generator hall. In addition, there is a small concrete pad on the east side of the turbine hall that would likely serve as a base for a transformer yard. We have not observed the installation cooling-water makeup tanks expected for a reactor of this design.

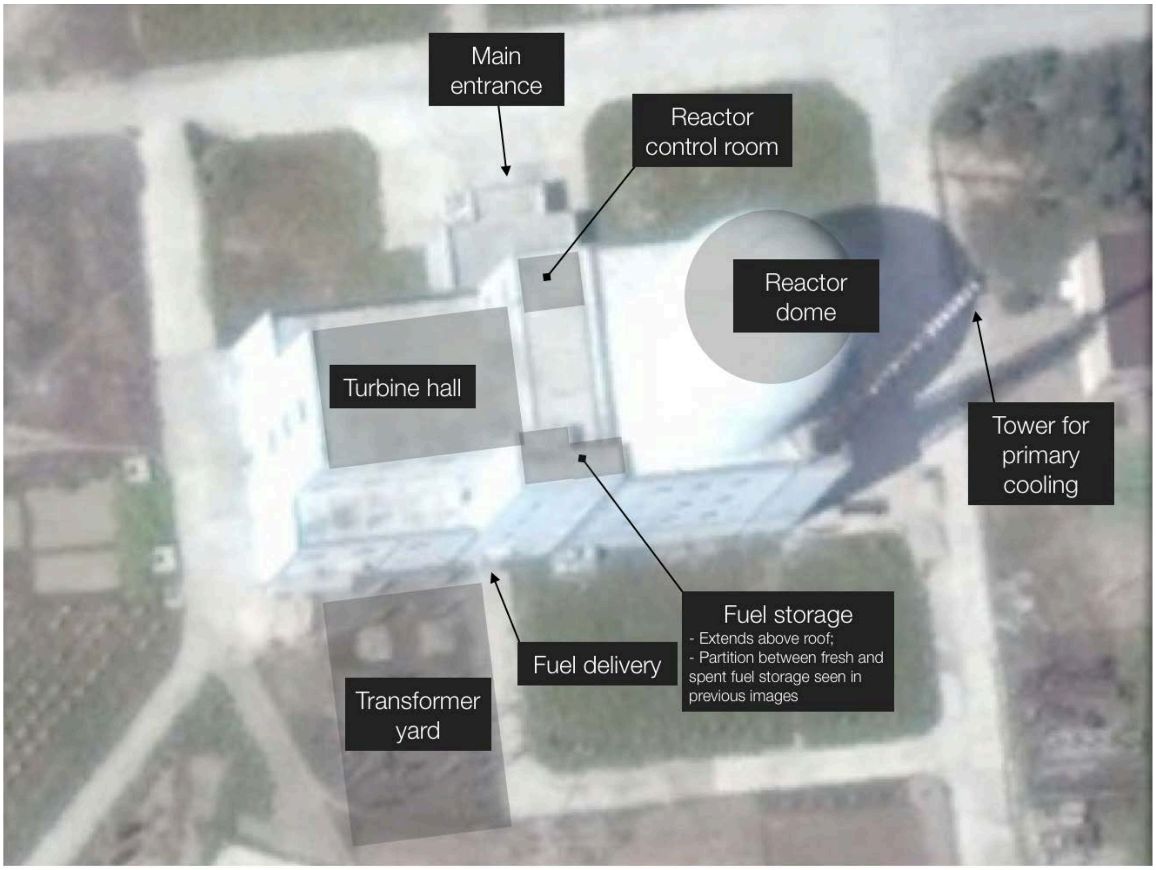

Fig. 5. Layout of the experimental light-water reactor (image from Google Earth, 9/24/2014; CR 2015 DigitalGlobe).

3. Future prospects and possible decommissioning

The ELWR is not yet operational as of the end of 2015. From external appearances, the reactor seems completed, and the recent installation of the external step-up transformer and transmission equipment imply that start up may be imminent. However, given that the experimental nature of the ELWR, startup delays are perhaps expected. Possible explanations for the delay include:

- Construction, completion and testing of all internal reactor systems may be continuing, particularly the instrumentation and control system;

- Difficulties in obtaining sufficient supply of LEU fuel from the enrichment plant, and in manufacturing ceramic UO_2 fuel assemblies in a new fuel fabrication plant located elsewhere in the Yongbyon complex;
- Deciding on what cladding to utilize and developing necessary cladding materials, along with gaining forming and welding experience;
- Uncertainties about adequate steady-state supply of cooling water from the Kuryong River (see Appendix 1);
- Start up and testing of a new type of reactor, by inexperienced engineers, may be taking longer than expected.

Given that this is a completely new design not yet operated in North Korea, with limited operator training and lack of experience in the operation of the safety regulatory system operations, imply that even if the reactor start-up is successful, it is no guarantee of sustained long-term safe operation of the ELWR. Continued vigilance on the part of Yongbyon operators will be required to check against any indications of a potential operational mishap. In case of a political settlement of the North Korean nuclear crisis, a decision will have to be made as to what to do with the ELWR. North Korean leadership intended the ELWR to be the first step toward a larger power reactor program, designed to help mitigate its electricity problem. That option appears rather unlikely. It may be possible, however, to have North Korea operate this reactor for several years until it can get help from other parties to build externally-supplied commercial power reactors; something along the lines of the KEDO arrangement. In any case, we have heard directly from the North Koreans that keeping some nuclear assets in their country is very important for them symbolically, and as a fallback position if negotiations fail. During the Stanford delegation trips, Hecker was told several times "how can we explain decades of expenditures on nuclear technologies and wind up with nothing at the end?"

Keeping the ELWR in operation in case an agreement is reached raises a potential proliferation concern. That is, could North Korea use the reactor to produce Pu for a weapons program, either clandestinely or after breaking out of an agreement? All uranium-fueled reactors produce Pu. The ELWR is estimated to produce approximately 10 to 15 kg under normal operation. However, the isotopic composition of the spent fuel is not well suited for bomb fuel. Clandestine Pu production is not possible because IAEA inspections would clearly show any violations. In the case of breakout, it is possible to divert the reactor from run cycles that are ideal for electricity production to short burn cycles that produce Pu more suitable for bomb fuel. Such operations can be readily detected by overhead satellite imagery. It is also possible to load a natural uranium blanket in the reactor and expose it to neutrons to produce Pu. In addition, it would be possible to produce tritium in Li-6 targets. Such operations would be more difficult to detect.

In the event that a decision is taken to dismantle the ELWR, there will be several decommissioning challenges not previously encountered at Yongbyon. In particular:

- LWRs operate to higher burnup, resulting in higher radioactivity of the spent fuel. These will present new problems in terms of transport;

- The Radiochemical Laboratory was originally configured to process low-burnup MAGNOX-type fuels. Since LWR spent fuel can be stored indefinitely, it is not clear that DPRK will reconfigure the reprocessing facility to handle high-burnup ceramic oxide fuel elements and their (likely) stainless-steel cladding. The higher quantities of plutonium in the ELWR spent fuel may present criticality safety challenges;
- Accumulation of low-level waste ("radioactive crud") from the primary coolant cleanup ("polishing") system will require storage in the reactor building as well as volume reduction and eventual disposal;
- Eventually, additional radiation-contaminated heavy components of the primary nuclear supply system (heavy pipes, pumps, steam generators, etc.)

These decommissioning issues will pose significant challenges, but are not categorically more difficult than other challenges encountered at Yongbyon. Yongbyon engineering talent, if available, will be a substantial asset in meeting these challenges, given their experience with the facilities themselves. The only area where qualitatively distinct technical challenges might emerge is the prospective reprocessing of spent LEU fuel elements. It will likely be advisable to reprocess these elements *at* Yongbyon, in order to secure their Pu content without the difficulty of transporting spent fuel and handling its final disposition. Depending on the political situation, the reprocessed Pu can then be shipped out of North Korea, or temporarily kept there under IAEA safeguards.

5. Uranium Enrichment

The Uranium Enrichment Workshop (UEW) at Yongbyon was revealed to outsiders for the first time when the Stanford delegation visited Yongbyon in November of 2010. North Korean officials invited Hecker and colleagues to tour a modern, small-industrial-scale enrichment facility containing 2,000 centrifuges. The facility had recently been completed in a renovated building (Building 4) that previously housed North Korea's metal fuel-rod fabrication plant. While the North Koreans had denied any work on centrifuge enrichment during the six of the previous Stanford delegation visits, it was clear from the sophistication and scale of the new facility -- and the fact that it had been constructed in less than two years -- that there must have been previous enrichment work dating back many years. Centrifuges manufacturing for the UEW might also have started in late 2008 or 2009, as discussed in Appendix 2. We will detail Hecker's previous assessments of uranium enrichment below. It was also clear that the suspected Pakistani connection had taken place, as the centrifuge design resembled the Pakistan's P-2 centrifuge. During the visit, North Korean officials claimed that the facility was operational and configured to produce LEU for the ELWR then under construction.

Since the revelation of the UEW, analysts have focused on estimating the enrichment capacity of the known site, along with that of suspected clandestine sites, and have speculated about how the enrichment program figures into North Korea's burgeoning nuclear weapons program. We would stress that North Korea's enrichment program is their new nuclear wild card. A capability to enrich uranium introduces dramatic uncertainty into any estimate of the North's nuclear future, and the truth is that we know very little about the extent of that capability. It is also difficult to predict how their enrichment capacity may grow, and how it will be used in the future. This section will sketch our limited knowledge of the North's enrichment program, and then move on to highlight the limitations of that understanding.

5.1 What we know about the uranium enrichment workshop

At the time of the Stanford visit, the enrichment workshop was a two-story building about 120 meters long by 16 meters wide. The centrifuges were located on the first floor in two high bays, each bay of having approximate dimensions of 50-by-15 meters, and containing three cascades each. The control room and observation deck were located on the second floor of the facility at its mid-point. The cascades in each bay were arrayed in three lines of centrifuge pairs, each line containing about 330 machines.[30] These observations are summarized in a rough schematic of the facility in Fig. 6.[31]

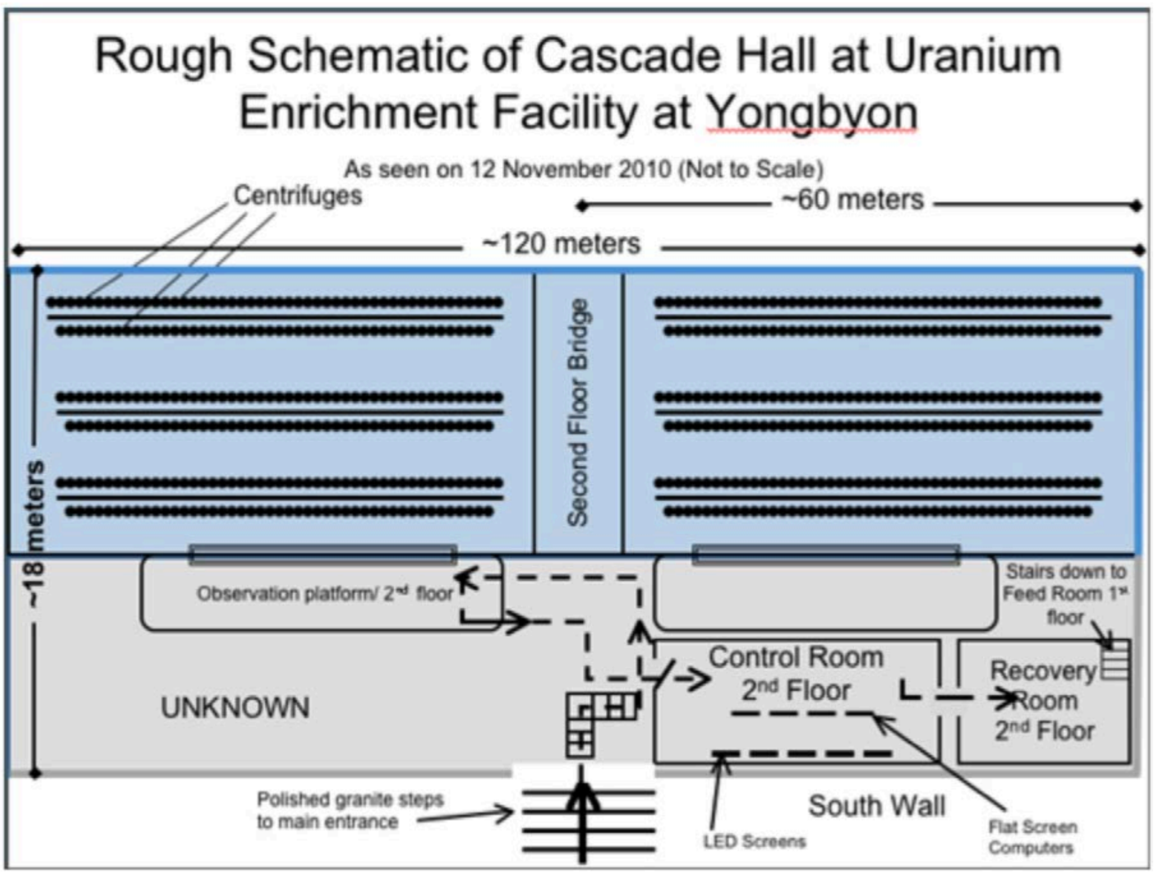

Fig. 6. Approximate layout of the uranium enrichment workshop (UEW) during the Stanford delegation visit in 2010.

[30] These observations are based on Hecker, 2010, Op. cit.
[31] Drawing from Niko Milonopoulos, et al., "North Korea from 30,000 feet", Bulletin of Atomic Scientists, 6 January 2012.

Table 2 lists our best estimates for some important technical characteristics of the UEW. As can be seen, nearly all of the information is drawn from statements made during the Stanford visit by the facility's chief process engineer (CE). As reported by the Stanford delegation, he was reluctant to give detailed information about the facility, and gave short responses to most questions. Where possible, the delegation was careful to check the consistency of the CE's answers with visual inspection, and we can also base some estimates on known attributes of the Urenco centrifuges that were the precursors North Korea's centrifuges. In any case, it is important to highlight the extreme limitations on what we know about the facility.

Table 2. Estimated properties of the uranium enrichment workshop.

Property	*Estimate*	*Data/reasoning*
Number of centrifuges	~2000	CE's indication to Hecker in 2010; consistent with visual inspection
Cascade layout	6 x 330-centrifuge cascades	CE's ind. 2010; consistent with visual inspection; consistent with Pakistani practice
Stated facility enrichment capacity	8,000 kg-SWU / year	CE's ind. 2010; slightly lower than G-2 performance ratings under optimal performance
Centrifuge type	P-2 type; supercritical centrifuge	CE's ind. 2010; resemblance to G-2; known collaboration with A.Q. Kahn
Rotor material	Maraging steel (grade unknown)	CE indicated "alloy containing iron"
Casing material	Aluminum (likely 6061-T6)	CE ind. 2020; consistent with visual inspection;
Approx. centrifuge dimensions	20cm dia.; < 180cm length; (may have been 150cm with pedestal)	CE's ind. 2020; consistent with visual inspection
Bellows arrangement	Single bellows	CE's ind. 2020; consistent P-2 and G-2 models
Enrichment rate per centrifuge	4 kg-SWU / year	CE's ind. 2010; slightly lower than G-2 performance ratings under optimal performance
Stated enrichment level	Average 3.5 % ^{235}U product (2.2-4% across core); 0.27% ^{235}U tails	CE's ind. 2010; consistent with fuel for LWR

The centrifuges themselves appear to resemble to the Pakistani P-2 model, which is a supercritical centrifuge based on Urenco's G-2 centrifuge model. The CE indicated that they were indigenously produced, but resemble those at Urenco's Almelo facility, which contains G-2 centrifuges (supporting the resemblance to P-2 centrifuges). He further indicated that their centrifuges were *not* P-1 centrifuges. He did not provide the delegation with detailed dimension or design information. The limited information given was consistent with visual inspection by the delegation. Each rotor was said to be divided into two equal sections by a single bellows, and was contained in a smooth aluminum casing without external cooling coils. When asked about the materials for the centrifuge rotor, the CE indicated that they were of an alloy containing iron, and this implies maraging steel rotors (also consistent with P-2 design). It was assumed that this would be Grade 350 maraging steel, which is typical for G-2 and P-2 rotors. However, this grade is very difficult to produce and it is doubtful that the DPRK has that capacity. Although it is believed that the DPRK imported some quantities of 350 maraging steel, it may also be augmenting that with domestically produced 250 maraging steel. Three small stainless steel tubes were seen to protrude from the top of each centrifuge, consistent with expected feed, product and waste streams.

In the control room, the delegation observed five large panels with modern LED displays, several computers and four flat-panel displays. Unfortunately, there was not sufficient time to glean much information from these displays, which showed what appeared to be flow diagrams and other data. The product-recovery room was located on the second floor near the control room, and it contained two operator personnel, two flat-screen displays and lots of tanks and plumbing. There were small, galvanized-steel panels and small tanks, along with a single large tank, oriented horizontally and approximately one meter in diameter by two meters in length.

The CE indicated that the facility had been finished shortly prior to the visit, and that during the visit it was enriching uranium to levels of 3.5% ^{235}U (with a range of 2.2 to 4% as requested by the reactor engineers). It was not possible for the delegation to verify these claims. In addition, he stated an enrichment capacity of 8,000 kg-SWU/year, or about 4 kg-SWU/year per machine. If accurate, this capacity would be enough to produce 2 tons of LEU per year, which is consistent with the stated requirements of the ELWR, the core of which was said to contain 4 tons of oxide fuel. The same capacity would produce 40 kg of highly enriched uranium (HEU) (90% ^{235}U) per year if the facility were configured to produce HEU, which is certainly possible, but unlikely at the time the delegation was there.

In late 2013, the building housing the UEW was expanded by an additional 14-meter-wide section extending the ~100-meter length of the original building. However, it is not clear how many centrifuges, if any, had been added to this additional floor space. Figure 7 shows the building housing the UEW in 2010, and in 2014 after the 2013 expansion.

Fig. 7. North Korea's uranium UEW in 2010 (left) and after being expanded in 2013 (right) (images from Google Earth, 2/17/2007 and 9/24/2014; CR 2015 DigitalGlobe)

5.2 Questions about the uranium enrichment program

We do not know the number of centrifuges North Korea might possess *beyond* those observed by the Stanford delegation in 2010. At a minimum, the speed with which the facility was constructed[32] indicates that some sort of pilot facility must have preceded the Yongbyon UEW. In order to study intra- and inter-cascade dynamics, such a pilot plant would need to contain at least two cascades, or at least 660 centrifuges. In addition, the expansion of the building observed in 2013 implies that the enrichment facility could have doubled in size, but there is no confirming evidence to indicate that such an expansion occurred. Finally, it is generally believed that North Korea has a clandestine, production-scale enrichment plant -- perhaps similar in size to the known plant at Yongbyon -- that could function as a hedge in the event of future inspections at Yongbyon. These issues are discussed in greater detail in Appendix 2.

The final set of questions address what North Korea hopes to achieve with its enrichment capabilities. In the case that the stated 8,000 kg-SWU enrichment capacity is correct, North Korea would have been able to produce enough LEU for up to 2.5 full loads fuel for the ELWR by the end of 2015, even though the reactor has not yet begun to operate. It is unlikely that the facility would be left to sit idle, and it would take little effort to re-route the plumbing to produce HEU once the fuel enrichment obligations for the ELWR would have been fulfilled. In addition, if there is a clandestine facility, the Yongbyon plant could continue enriching up to 3.5% as stated, and ship some of that product to the clandestine location in order to further enrich up to higher levels. This would allow North Korea to avoid producing traces of HEU at Yongbyon that would be detectable in the event of future inspections. While it is unclear whether North Korea has developed a warhead design that would use HEU, they indicated in 2013 that they would "re-adjust" their nuclear program to strengthen their deterrent, implying that the enrichment capability would be redirected toward weapons applications.

Taken together, these questions express the great uncertainty that North Korea's enrichment capability introduces to an understanding of its nuclear program. In the absence of direct data on the number and performance of North Korea's centrifuges at Yongbyon as well as elsewhere, the only way to constrain this uncertainty is to consider the materials North Korea would need to make those centrifuges. Table 3, reproduced from Bistline et al.[33] presents a list of the capabilities and materials that are necessary to produce supercritical centrifuges. Of these thirty components, three are believed to be the most likely bottlenecks on North Korea's capacity to produce centrifuges: the availability of pivot bearings, of high-strength aluminum (or aluminum tubes), and of maraging steel (250 or 350 grade).

Table 3. Components, capabilities and materials required to produce supercritical centrifuges

[32] It was originally the location of the fuel fabrication activities associated with the 5MWe reactor, and hence associated disablement measures took place there in accordance with the February 13, 20007 agreement. U.S. and IAEA officials were present to verify these measures as late as 2009.

[33] John Bistline, et al. "A Bayesian Model to Assess the Size of North Korea's Uranium Enrichment Program", Science and Global Security, vol. 23, pp. 71-100, 2015.

Centrifuge components	*Manufacturing and testing*	*Materials*
Baffles	CNC lathes	**High-strength aluminum**
Centrifuge housings	Controller units	Araldite potting epoxy
Coolant pipes	Flow-forming machines	**Maraging steel (250 or 350 grade)**
End caps	Flow meters	PFPE oils
Frequency modulators	Grinders	Stainless steel
Molecular pumps	Magnetometers	
Pivot bearings	Mass spectrometers	
Bellows	Milling machines	
Rotor tubes	Pressure transducers	
Scoops	Rotor balancing equipment	
Stators	Vacuum pumps	

5.3 A brief history of North Korea's uranium enrichment program

We suspect that North Korea started a uranium centrifuge program early, perhaps in the 1970s or 1980s, but then did not try to accelerate the effort until their dealings with A.Q. Khan in the 1990s during the Agreed Framework. In retrospect, the U.S. government accusation in 2002 of North Korea conducting a clandestine uranium enrichment program was correct, although the decision to break off the Agreed Framework backfired since Pyongyang proceeded to build Pu bombs in a very short time.[34] Albright and Brannan[35] have presented a detailed analysis of the status of North Korea's uranium enrichment program just before the Stanford delegation visit in November 2010. Albright and Brannan demonstrate a clear pattern of cooperation and exchange between North Korea and Pakistan, including crucial elements such as on-site training of North Korean technical specialists at the Khan Research Laboratory. They also show troubling procurement schemes, first with European companies and then with commercial entities in China. However, all analysts were surprised at the extent of the centrifuge program revealed in November 2010.

Understanding North Korea's motivation to develop uranium enrichment is even more difficult. Its domestic nuclear power program was based on the development of gas-cooled reactors, although that came to an end with the Agreed Framework. The only one of the GCRs that became operational was the 5MWe reactor, which was too small to make it useful for commercial electricity generation. It was used instead to produce bomb-grade Pu. It appears that North Korea was prepared several times to trade this bomb-fuel producing reactor for the provision of electricity-generating LWRs. However, by the time of the November 2010 visit, the Stanford delegation was told by North Korea officials, "We have given up; we will do it on our own." The officials remarked that in April 2009 they announced their intention to build an LWR and to make their own fuel, including enrichment. They made the point that no one, including Hecker believed them at the time. With the construction of the ELWR they can claim with some justification

[34] See Chinoy, 2008, Op. cit.
[35] David Albright and Paul Brannan, "Taking Stock: North Korea's Uranium Enrichment Program", Institute for Science and International Security, 2010, http://isis-online.org/uploads/isis-reports/documents/ISIS_DPRK_UEP.pdf.

that the uranium enrichment program is an integral step toward an indigenous LWR and a nuclear electricity program. It is also, of course, the second route to the bomb.

As we try to reconstruct when North Korea decided to accelerate and announce its centrifuge program, we are reminded that through early 2007 Vice Minister Kim Kye-gwan was still trying to convince the U.S. government to supply an LWR and indicated to Hecker that they were willing to have the fuel enriched elsewhere and return to spent fuel. In fact, during one of the meetings with the Stanford delegation, Kim even said that if you are so concerned about the potential proliferation danger, then we can jointly operate the LWR to give the United States an on-site presence. During all of the meetings through 2007 with the Stanford delegation, Kim denied the existence of an uranium enrichment program. However, during several meetings he expressed his frustration that he was unable to get good information from his own government. The denial was necessary because in the absence of a domestic LWR program, the only use for enriched uranium would be for a bomb program.

However, during the August 2007 visit, Kim told the Stanford delegation that if the United States continues to refuse to supply an LWR, then North Korea would go its own way. He said, "if we do so, then we will have to do enrichment ourselves." This was the first hint that North Korean officials gave the Stanford delegation about the potential of building their own LWR and of having to develop enrichment capabilities. As mentioned in the ELWR section above, after the April 2009 UNSC condemnation for North Korea's rocket launch, Pyongyang announced that it would build its own LWR and make its own fuel. They expelled the IAEA inspectors in April 2009 and by September announced success in their first enrichment trials. By November 2010, they toured the Stanford delegation through the 2,000-centrifuge facility in Yongbyon.

Based on these timelines, we can draw several conclusions. North Korean officials denied an enrichment program through 2008. It is simply impossible to have developed centrifuge capabilities from scratch between the time of the announcement in April 2009 until their declaration of success in September. Moreover, it is impossible to have developed a working centrifuge facility of 2,000 centrifuges between April 2009 and November 2010. A centrifuges manufacturing facility would have had to produce the requisite centrifuges even before they were installed in the UEW in Yongbyon. Working backwards from what the delegation saw in November 2010, we conclude that North Korea had an active centrifuge program for likely more than a decade. Some number of cascades of P-2 centrifuges must have been made operational at a clandestine facility to test centrifuge operating parameters and cascade operations. Once cascade operations with a specific centrifuge design and arrangement was demonstrated to work, which may have been around 2008, then North Korea must have fabricated the centrifuges installed at Yongbyon (it is possible that one or two of the cascades were actually transferred to the Yongbyon facility). We do know that the physical facility for the Uranium Enrichment Workshop was not begun until after April 2009 because the IAEA inspectors had access to Building 4, which was later gutted, supplied with a new roof, and outfitted with the centrifuges and ancillary equipment.

5.4 Possible decommissioning of the uranium enrichment workshop

In principle, it should not be too difficult to decommission a centrifuge-based uranium enrichment plant. ^{235}U is an alpha emitter and is relatively easily contained and decontaminated. No other major nuclear contaminants exist that could pose radioactive hazards during the decontamination process. Greater chemical hazard might exist due to the presence of highly corrosive fluorides, particularly hydrofluoric acid used in the production of UF_6. UF_6 must be handled in accordance with radio-toxicity standards and taking into account its corrosive nature, though North Korea will have accumulated a significant body of experience in handling this material by the time decommissioning happens. No experience in the decommissioning of operating centrifuge enrichment plants exists except, possibly at Urenco and in the Russian enrichment complex operated by Rosatom. In both cases existing centrifuge halls were converted from using earlier generation centrifuges to the use of more modern and efficient machines. A similar experience exists in Japan Nuclear Fuels Corporation (JNFL) enrichment plant in Rokkasho Mura and in the KRL in Pakistan. All these cases represent partial decommissioning experience dealing with the replacement of old vintage centrifuges rather a complete dismantlement of centrifuge enrichment facilities.

Nevertheless there exists a significant body of experience in decommissioning much larger gaseous diffusion enrichment plants, particularly in the U.S. (Oak Ridge K-25 Plant) and in the U.K. Diffusion plant in Capenhurst, and the French HEU enrichment plant in Pierrellatte and Tricastin (still in process), and possibly Russian diffusion enrichment plants in the Ural Mountains region. These larger plants have operated much longer than centrifuge enrichment plants which has resulted in greater accumulation of contaminants in various enrichment plant components (diffusion chambers, compressors, pumps, etc.). The physical sizes of some of these components are much larger than the sizes of any equipment items likely to be found in a centrifuge enrichment plant. Yet the decommissioning of such large (and more contaminated) gaseous diffusion plants has been successfully completed and documented.

All of the above leads to the conclusion that should it be decided to decommission the Yongbyon centrifuges enrichment plant, and possibly other enrichment plants in North Korea, such operation will not be too difficult from a technical perspective, and could possibly be successfully accomplished. The more salient question is a political one; that is, should one decommission the relatively new and modern North Korea enrichment plants or could these plants be modified and re-purposed for LEU production only and be operated for civilian purposes with international inspection or with multinational ownership and operations.

6. Fuel-fabrication facilities

In addition to the emergence of the UEW, shifting to an LWR fuel cycle has entailed significant changes at the Fuel Fabrication Plant (FFP). Since the FFP was built to provide fuel for the North's GCR complex, including the 50MWe and 200MWe GCRs, the FFP has a much larger capacity than is needed for the 5MWe. Hence, it is natural that many of the FFP buildings would be repurposed in order to serve the needs of the ELWR. An aerial view of the FFP as it exists in 2015 is shown in Figure 8 below. This section describes the changing function of the FFPs various buildings. We begin by describing the pre-AF fuel-fabrication capability, drawing mainly from data acquired by the IAEA during the facility freeze associated with the AF. Then we describe the revival of the facility in 2003, and subsequent disablement measures associated with the February 13, 2007 agreement. Then we consider the changes that would be needed to produce fuel for the new ELWR.

Fig. 8. Overview of the fuel fabrication complex (August 22, 2015).

6.1 Fuel fabrication before the Agreed Framework

The FFP was built in the early nineties to produce 100 MT/year MAGNOX fuel for the GCR complex.[36] The raw material for this fuel was uranium yellowcake form (U_3O_8) produced at the uranium mining and milling facilities located elsewhere in North Korea. Figure 9 shows the layout of the facility prior to the advent of the UEW (which was later built in Building 4), along with annotation of the material flow for the production of MAGNOX fuel. Yellowcake was brought by rail into Building 1, where it was reduced from U_3O_8 to UO_3 and then further to UO_2. The UO_2 was then brought to Building 2 to be purified and converted[37] to UF_4 (using Hydrofluoric acid produced in the building located to the southwest (labeled “HF production” in the figure). Building 2 also included waste recovery and recycling lines. Further reduction of UF_4 to metallic form was carried out in Building 3, by mixing UF_4 with magnesium chips and heating in a reduction furnace to 600 deg. C. At least four furnaces were available for this uranium reduction and melting step. The metallic uranium was alloyed with 0.5% aluminum and then converted to uranium rods. These rods would then be transported to Building 4 to be assembled into the final MAGNOX-clad GCR fuel elements. The completed fuel elements were stored in Building 6.[38]

[36] See Albright and O’Neill, 2000, Op. cit.
[37] Conversion to UF_4 is conducted in another two-stage fluidized bed by contacting with hydrofluoric acid at 500 degrees C.
[38] See Albright and O’Neill, 2000, Op. cit.

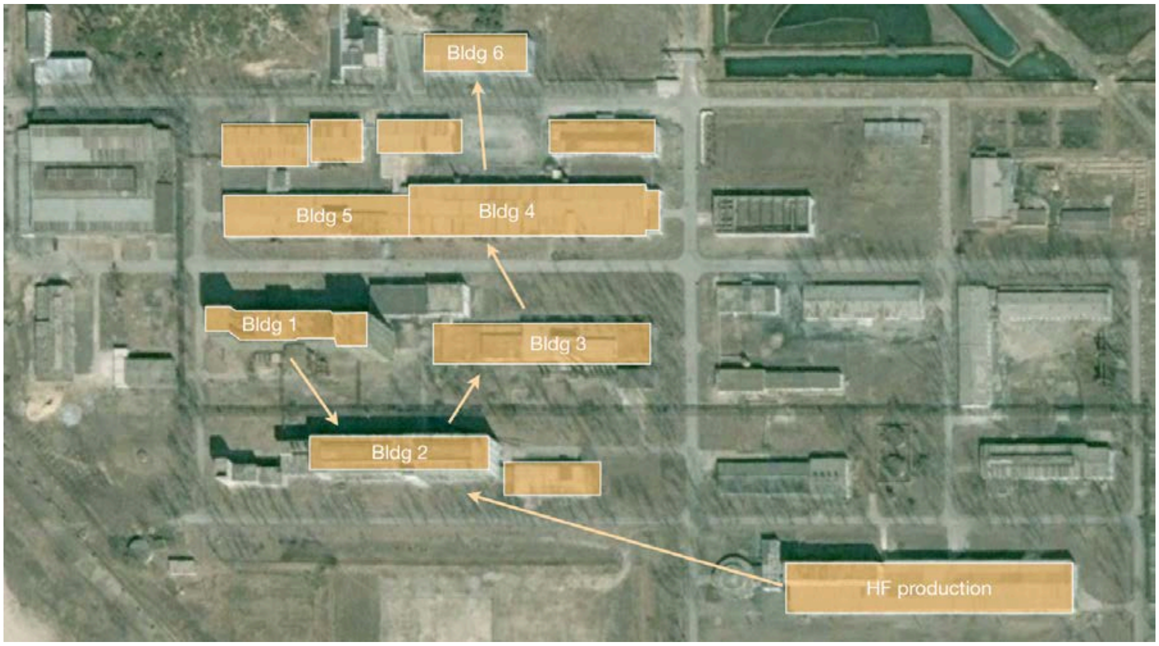

Fig. 9. Material flow for the production of MAGNOX fuel at the fuel fabrication complex prior to the Agreed Framework (image from Google Earth, 3/27/2005, CR 2015 DigitalGlobe).

6.2 Reconstitution and disablement measures

Considerable degradation occurred at the FFP during the 1994-2002 freeze. This degradation imposed some obstacles when North Korea sought to revive its capability to produce fuel for the 5MWe reactor. In particular, buildings associated with hydro fluorination were corroded, and the hydro fluorination line had to be rebuilt in a separate building.[39] This delayed the resumption of MAGNOX-fuel production until 2007.

Disablement measures associated with the February 13, 2007 agreement took place late in 2007, including:

- Removal and storage of (three) uranium ore concentrate dissolver tanks;
- Removal and storage of (seven) uranium conversion furnaces, including storage of refractory bricks and mortar sand;
- Removal and storage of metal casting furnaces and associated vacuum system;
- Removal and storage of eight machining lathes;
- Storage of remaining UO_3 powder in bags monitored by IAEA (nearly five tons of powder);
- Disablement of fresh, unclad fuel rods that were fabricated prior to 1994 and stored at the FFP.

[39] The first attempt was made in the existing building, but was quite primitive as reported by the IAEA. During the 2010 visit to Yongbyon, Section Head Ri Yong-ho told Hecker that they now have the anhydrous capability in another building on site, but not specifying the building.

It is believed that these measures were reversed after North Korea rescinded the February 13 agreement in 2009. However, Building 4 was gutted and re-fitted as the modern UEW centrifuge facility. The equipment from Building 4 was likely stored somewhere in the FFP and was likely subsequently installed in some other building to produce fresh metallic fuel for the 5MWe reactor.

6.3 Production of light-water reactor fuel

After IAEA inspectors were ejected from Yongbyon in 2009, North Korea began renovating and repurposing buildings in the FFP. The major change was to refurbish Building 4 and turn it into the UEW. Several additional capabilities would be required to produce LWR fuel. These include:

- *Uranium conversion*: uranium enrichment requires uranium in the form of UF_6. Hence, a facility is needed to convert UF_4 into UF_6 to be enriched. This could take place in one of three renovated buildings on the east side of the FFP. Hecker was told in 2010, that the fluorination is now done with an anhydrous process and it is done in one of the buildings on this site. That site has not yet been positively identified. North Korea had previously denied having produced UF_6 along with its denial of an enrichment program. Yet, credible reports following Libya's termination of its enrichment program indicate that North Korea supplied UF_6 to the clandestine Libyan enrichment program. Hence, North Korea must have had the capacity to UF_4 into UF_6 prior to 2002.[40]
- *Reconversion into oxide*: once enriched, UF_6 must be reconverted into oxide for the production of ceramic fuel for the ELWR. This likely takes place in one of the repurposed buildings at the FFP. A reasonable location would be Building 3, which was renovated in 2011-2012.
- *Fuel-rod fabrication*: UO_2 must be sintered into pellets and machined to the proper dimensions; coated with a ceramic coating and loaded into metal cladding to produce the fuel rods. LWRs typically use zircaloy metal cladding. However, as noted above, it is not known if North Korea has the ability to produce zircaloy. Stainless steel cladding is an alternative, but is less attractive for good reactor performance because of greater neutron absorption. North Korea should be able to manufacture stainless steel cladding because it had produced aluminum cladding for the MAGNOX fuel. Noble gas is then introduced. This may also take place in Building 3, which was the old metallurgy building.
- *Increased HF demand*: the old hydrofluoric acid production plant (south-eastern corner of complex) has been upgraded to meet the increased demand for HF. A new building constructed just south may be related to this.

No positive identification of these facilities has been possible in the absence of IAEA presence on the ground at Yongbyon.

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[40] Jeffrey Lewis, "North Korea sold UF6 to Libya," Arms Control Wonk, Feb. 2, 2005. http://www.armscontrolwonk.com/archive/200415/north-korea-sold-uf6-to-libya/

6.4 Potential additional fuel fabrication facilities in Yongbyon outside of the FFP

As pointed out above, Yongbyon officials decided to repurpose the metal fuel fabrication facilities in Building 4 into the UEW. However, since they have restarted the 5MWe reactor, they once again required the equipment previously located in Building 4 for the fabrication of additional fuel rods for the reactor. It is possible that two additional facilities have been completed to support fuel fabrication activities – one for the 5 MWe reactor and one for new space for fuel elements for the ELWR. The two suspect facilities are located in the area close to the location of the reactors (the northern part of center west of the Kuryong river) rather than in the southern part of the center, east of the river, where most of the major fuel-cycle facilities are located. Information regarding these facilities was obtained only from satellite imagery. Since no on-site confirmation exists, this assessment is still speculative. A top view of the northern part of the Yongbyon center depicting the two new suspect fabrication facilities is shown in Figure 10.

The imagery indicates that the site of the pilot fuel fabrication facility, just north of the 5 MWe reactor, which was used in the 1980's to produce the original fuel batches for the reactor before the completion of the FFP, appears to have been reactivated and refurbished. We estimate that this facility has been re-purposed to carry out the final steps of the 5MWe fuel elements fabrication removed from Buildings 4 and 5 of the FFP. A new large-sized facility was also constructed in the area north of this pilot fuel fabrication facility, and south of the IRT-2000 complex. This facility oriented in a north-south direction includes a large high bay in the center and two adjacent lower bays on the two sides of the general high bay. We assume that this facility is planned as the final fabrication plant for the ELWR and for fuel elements for any follow-on LWRs.

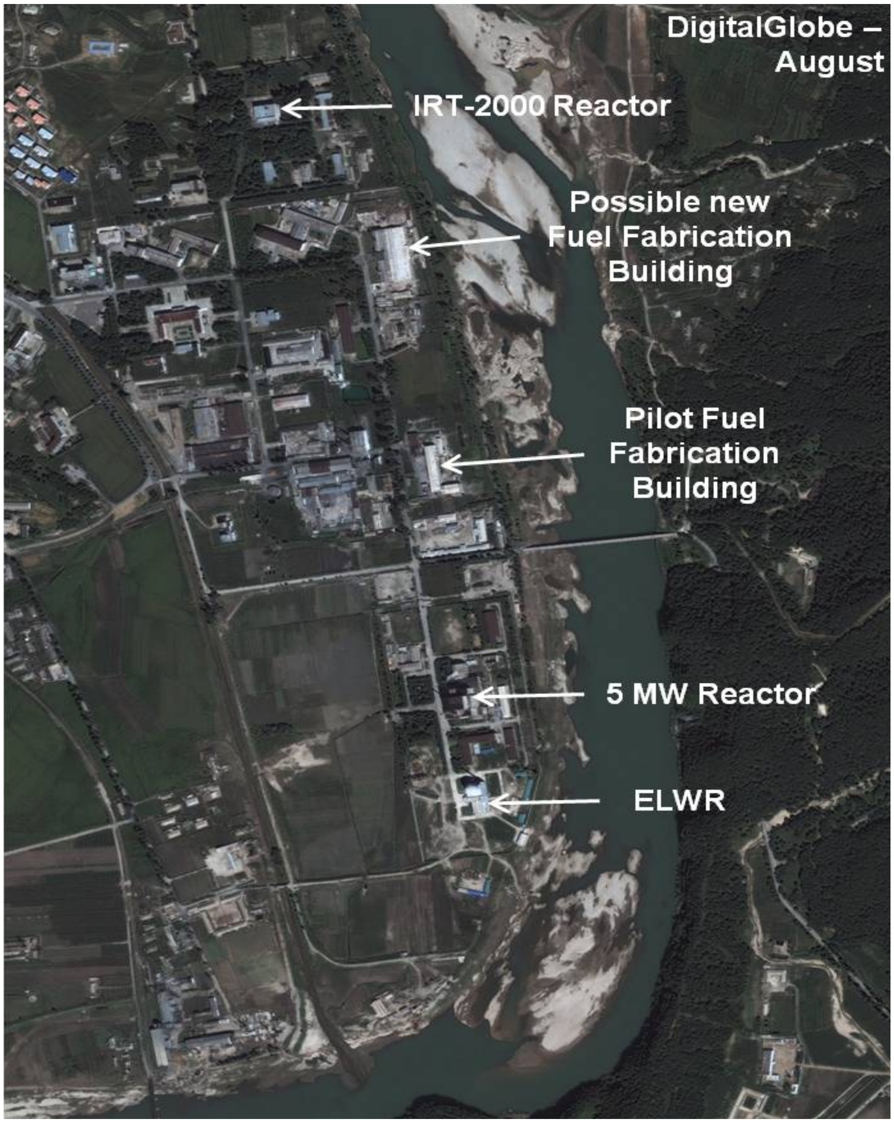

Fig. 10. Overview of suspect new fabrication plants in Yongbyon

6.5 Future prospects and decommissioning

There are several refurbished and new facilities associated with the front end of both the GCR and LWR fuel cycles, and these may have taken place at the FFP or at other unknown locations. Discussion of future use or possible decommissioning will require mapping these facilities. But since no highly radioactive materials are handled in the fuel fabrication process (with the exception of alpha-emitting ^{235}U), decommissioning should be relatively straightforward from a radiation-safety standpoint. However, decommissioning of hydro-fluorination facilities would involve handling of corrosive chemicals. Any LEU or HEU located at the FFP would require safeguards procedures and accounting. Some equipment contaminated with LEU or HEU would be designated low-level waste.

7. Back end of fuel cycle

The Radiochemical Laboratory (RCL) at Yongbyon is a fully functional reprocessing plant with capacity of 110 MTHM/year. The design of the plant appears to be patterned after the publicly available technical data for the EUROCHEMIC (European Company for Chemical Processing of Irradiated Fuels) plant located in Mol, Belgium.[41] It employs a modified version of the PUREX (Pu-U Redox Extraction) process. When construction began, sometime between 1987 and 1989, it was originally intended to service both the 5MWe and 50MWe GCRs, and hence has two parallel processing lines. But in practice, only one processing line is typically used since the 50MWe reactor was never completed, with the adjacent line in standby as backup. The plant was about 75% complete at the time of the first nuclear crisis, with the first line completed in 1990. Further expansion was frozen by the AF in 1994, but resumed in 2003 shortly after the AF was abandoned.

As pointed out previously, spent MAGNOX fuel from the 5MWe reactor cannot be stored indefinitely, and *must* be reprocessed. In a dedicated nuclear energy program based on MAGNOX reactors, Pu from reprocessed spent fuel would end up as PuO_2, since this form is easy to store and may be useful for other energy applications. In a weapons program, a further step would be carried out to convert the PuO_2 into Pu metal for weaponization. While it is not certain that this final step was in place at the time of the first nuclear crisis in 1994, there is some evidence that it was. This evidence is outlined in detail by Albright and O'Neill.[42] In any case, it is clear that metallic Pu was produced after 2003. During the 2004 Stanford delegation visit to Yongbyon, Hecker was shown a 200-gram Pu piece that was said to have been produced in the facility. During the August 2007 visit, Hecker was allowed to visit the Pu laboratory, which was fully equipped with glove boxes and was said to be able to take Pu metal all the way through the alloying stage to deliver it for weaponization, said to be done off site.

Most of our knowledge about the RCL was obtained by pre-AF North Korean declarations to the IAEA, which were subsequently verified. IAEA inspectors had access to the RCL for the duration of the AF (1994 - 2002). After the AF fell apart in 2002, inspectors were ejected, and the RCL was quickly reconstituted and upgraded shortly thereafter. These upgrades increased the capacity of the RCL 30% to about 480 kg/day. Insight into the RCL was limited to that gained by the Stanford delegation visits in 2004, 2007 and 2008, and from satellite imagery. After the February 13, 2007 agreement, disablement measures were carried out at the RCL, and these were verified by IAEA and U.S. personnel. The Stanford delegation was able to verify these and take photographs during its February 2008 visit. These measures were reversed after the North rescinded the February 13 agreement in 2009, and inspectors have since been barred from the facility. An aerial view of the RCL obtained from satellite imagery is show in Figure 11. Our description of the RCL begins with the basic knowledge gained from the pre-AF data, combined with general knowledge about the PUREX process. Then, we discuss the reconstitution of the RCL after the AF, and the upgrades that were revealed to the Stanford delegation in 2004 and 2005. We then cover the disablement measures of 2007-2008, and their reversal in 2009. Finally, future prospects will be considered. While many

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[41] Albright and O'Neill, Op. cit.; Whang and Baldwin 2005 Op. cit.

[42] Albright and O'Neill, Op.cit.

have noted that the ELWR will produce Pu, this would require substantial changes to the RCL, but is not beyond the technical means of Yongbyon staff. On the other hand, there are few appreciable barriers to the continued reprocessing of spent fuel from the 5MWe GCR, as well as anything produced in targets at the ELWR. Decommissioning considerations will also be discussed.

Fig. 11. Overview of the radiochemical laboratory (RCL) complex.

7.1 Layout and operation of the radiochemical laboratory complex

The main building of the RCL is 192 meters long, 27 meters wide, and six stories high (see Fig. 12). It contains six processing cells on the ground floor, and three smaller-scale laboratory rooms on the upper floor. The processing 'hot' cells are protected by one-meter-thick concrete walls with leaded windows and master-slave manipulators. Several waste processing buildings and tanks surround the main building, as well as an adjoining analytical laboratory on the north end of the main building where several small-sized manipulator-operated shielded cells are used for analytic chemistry work. A coal-fired steam plant is located 0.7 km southeast of the RCL (not included in Figures 11 or 12), and process steam therefrom is carried by four parallel pipes (indicated by a dotted line in Fig. 12) into the RCL.[43]

[43] Whang and Baldwin, 2005, Op. cit.

Spent fuel is received from the 5MWe reactor at the fuel-reception building located just south of the main building. Lead casks holding the spent fuel are removed from a heavy shielded truck and lowered into a belowground transfer vehicle, and then transported through an underground tunnel that extends the length of the main reprocessing building. The reprocessing operation begins in the north-most hot cell, and fuel streams move thereafter from cell to cell in a southwardly direction. In the first (north-most) hot cell, the end fittings of each fuel element are sheared off (and consigned to waste). The MAGNOX cladding is then removed in a cladding dissolver using hot, dilute nitric acid. The uranium rods are then transferred to the fuel dissolver to be dissolved in hot, concentrated nitric acid. Volatile fission products, such as ^{85}Kr and ^{131}I are removed in this process, and are discharged into the atmosphere through a ventilation stack (increasing radiation levels around the site). The fuel in aqueous nitrate solution is then pumped to a separate hot cell where it enters a group of thirty mixer settlers, each with a capacity of 80 liters, for the first step of the PUREX separation process. It is contacted in a countercurrent flow with a stream of organic solvent -- 30% (vol.) tri-butyl-phosphate (TBP) in kerosene. This is where most of the uranium and Pu are extracted into the organic solution. Fission products are left in the nitrate solution, along with trace amounts of uranium-Pu mix.

In the next phase of the PUREX separation process, the uranium is stripped out of the uranium-Pu organic solvent with a stream of dilute nitric acid. The separated uranium stream is sent to the holding tank as process waste. The Pu is then stripped out of the organic solvent using a stream of aqueous nitrate solution containing hydroxylamine and hydrazine. The aqueous, partially purified nitrate solution containing separated Pu is then pumped into a following cell where the Pu is purified through an additional cycle of extraction into an organic phase (20% by volume TBP in kerosene) using twenty mixer-settlers, and then stripped by a diluted aqueous nitric acid solution. This represents the Pu purification step of the PUREX process.

The final step in the purification process occurs in a series of five shielded glove boxes located outside the Pu separation cell. In the first glove box, the Pu is further purified by ion exchange in stainless-steel columns containing DOWEX anion-exchange resin. The second glove box contains additional ion-exchange columns to separate out and recover the lost Pu back to the first separation box. Sample characterization measurements are carried out in the third glove box, and precipitate Pu is removed in the fourth glove box as Pu oxalate. The final glove box includes a furnace to dry and calcine the oxalate precipitate (450 deg. C) to produce a final product of pure PuO_2.[44]

[44] Albright and O'Neill, 2000, Op. cit.

Fig. 12. Layout of the radiochemical complex (image from Google Earth, 10/27/2014, CR 2015 DigitalGlobe).

7.2 Reconstituted plutonium production: 2002 – 2007

After the demise of the AF North Korea ejected IAEA inspectors and restarted the RCL in order to reprocess the 8,000 stored spent fuel elements that were stored in the cooling pool as part of the Agreed Framework. In addition, the Pu "finishing line" was established (or re-established, depending on whether it existed in 1994) to convert PuO_2 to Pu metal. During the first Stanford delegation visit to Yongbyon in 2004, North Korean scientists allowed Hecker to hold a sealed glass jar containing 200 grams of Pu metal from this reprocessing campaign. By the 2005 visit of the Stanford delegation, Director Ri Hong-sop told Hecker that the box-type mixer-settlers in the uranium-Pu co-extraction line were replaced with vertical pulsed-partition columns. This increased the daily processing rate by 30% above the nominal capacity of 480 kg/day. As they did not need the additional capacity, the reason for the substitution was that it had better efficiency for Pu extraction, leaving less in the waste stream. A second reprocessing campaign was carried out in 2005.

7.3 Implementation and reversal of disablement measures

A series of disablement measures were carried out in 2008 in accordance with the February 13, 2007 agreement. These measures included:

- Removing the drive mechanism for the trolley that moves the spent fuel casks from the fuel receiving building into the RCL;

- Cutting two of the pipes that carry process steam from the coal-powered steam plant (southeast of the RCL) into the RCL;
- Removing the crane and door actuators that permit the spent fuel casks to enter the reprocessing plant main building through the underground tunnel (extending the length of the reprocessing building;
- Removing the drive mechanisms for the cladding-shearing machines in the first (northern-most) hot cell of the reprocessing line.

These measures affected mechanical aspects of the RCL, and were therefore reversible. Hecker and his colleagues saw these measures during the February 2008 visit. They judged the measures to be serious, but also easily reversible. At the time the measures were to be carried out, the facility still contained 80 m^3 of high- and low-level waste that needed to be processed prior to storage. For this reason, the chemical-separations stages of the reprocessing line were left intact. The Pu finishing line was also not affected. After the North Korea rescinded the February 13 agreement in 2009, the disablement measures were reversed, and another reprocessing campaign was carried out in 2009.

7.4 Future prospects and possible decommissioning

The RCL appears to be in good working order and capable of continued operation for some time. The chemistry side includes many process equipment items operating in series and in parallel, which provides a high degree of flexibility for equipment to be replaced as required. The plant is planned for contact maintenance, which allows easy equipment replacement. If the 5MWe reactor continues to operate in future years, then the RCL will likely not be a limiting factor in Pu production.

The RCL is not prepared as is to reprocess spent fuel from the ELWR or other reactors based on that fuel cycle. LWR fuel is irradiated to much higher burnup levels, and this makes reprocessing more difficult, and the Pu less valuable for weapons. In addition, the spent fuel is in ceramic oxide, not metallic form, and is more difficult to dissolve. It is unlikely that DPRK will reprocess spent LWR fuel at the RCL for weaponization. On the other hand, in the event that the nuclear complex is dismantled, the Pu contained in any spent LWR fuel would still need to be secured for nonproliferation reasons. In this case, it may be easier to modify the RCL in order to extract the Pu than it would to transport spent fuel to another reprocessing location abroad. This would require substantial changes to both the mechanical front end and chemistry sections of the plant, and this would pose significant challenges. The front end would need to be modified to handle stainless-steel-clad (or potentially zircaloy-clad) fuel of different dimensions and hardness (than that from the 5MWe reactor). The chemistry section will also need to modification due to the greater concentrations of Pu and radioactive fission products in the spent fuel.

The most important issue in the event of a political agreement is whether or not the RCL would be shut down immediately to eliminate prospects of further reprocessing. It turns out that from a technical standpoint that would be unwise. During Hecker's visit to Yongbyon, he was told by Director Ri that they have not yet processed any of the high or low-level waste from the reprocessing campaigns. Ri said that they had done some limited experiments on vitrification for eventual disposition of the high-level waste, but did not proceed very far. Hence, the RCL will be needed to prepare the waste for storage or disposition. Without it, the eventual decommissioning of the facility would not be possible. In addition, although it may not be politically attractive to reprocess whatever spent fuel is in the pipeline at the time of a political settlement, it is again technically a much superior option to shipping out 8,000 fuel rods (containing 50 tons of spent fuel). It will be much simpler to either have the 10 kg or so of Pu under safeguards or ship it out of the country.

8. Plutonium production

The 5MWe reactor is North Korea's only significant source of Pu. While a small amount of Pu was produced at the IRT-2000 research reactor in the 1980s, this would have been less than a few kilograms, and most likely, much less. The 5MWe reactor is believed to be capable of producing 6 kg of WGPu for every year of continuous, optimal operation. Under normal operation for Pu production, a fuel core would be irradiated to an average burnup of about 635 MWth-d/T. The RCL originally had a through-put of 110 tons of spent uranium fuel per year, so a 50-tonne core from the 5MWe reactor can be reprocessed in less than six months. However, it is likely that the 5MWe reactor has almost never run under optimal conditions, and this adds uncertainty to any estimate of Pu production

After first achieving criticality in 1986, the 5MWe reactor is said to have had startup problems prior to 1991, including fuel-rod failures.[45] The first known shutdown was observed by U.S. intelligence via satellite imagery in 1989. Official estimates of the duration of the shutdown range from 70 - 100 days. It is unclear how much fuel was extracted during this shutdown. In particular, we do not know whether Yongbyon officials only removed damaged fuel elements, or a substantial part of the core for Pu extraction. During this time, Albright estimates that up to 9.5 kg of WGPu could have been in the entire core, and this serves as an upper bound for how much could have been removed in 1989.

The full-core discharge in 1994 was monitored by IAEA inspectors during its storage in the spent-fuel pool. The spent fuel was re-canned by a U.S. technical team during the Yongbyon freeze associated with the AF. But after the demise of the AF became in 2002, Yongbyon scientists removed the 1994 core from storage and reprocessed it in the first six months of 2003, yielding an estimated 20 - 30 kg of WGPu.[46] North Korean officials indicated that the WGPu would indeed be dedicated to weaponization. In 2004, the Stanford delegation was shown two jars that were said to contain samples of Pu product from this campaign. One jar was said to contain 150 grams of Pu oxalate powder and the second was said to contain 200 grams of Pu metal. These samples exhibited several characteristics consistent with DPRK claims, including: apparent density and heat generation; appearance (green color consistent with oxalate); color and surface characteristics of the cast Pu metal piece. The density of 15 to 16 g/cc as claimed by

[45] Albright and O'Neill, 2000, Op. cit..
[46] See Siegfried S. Hecker, "Report on North Korean Nuclear Program", 2006, https://cisac.fsi.stanford.edu/sites/default/files/DPRK-report-Hecker-06-1.pdf.

Director Ri is consistent with alloyed Pu in the delta phase, which makes it possible to cast and machine plutonium parts.

In addition to reprocessing the old spent fuel from storage, Yongbyon officials reloaded the 5MWe reactor with fresh fuel, and restarted the reactor in early 2003. Operation at 25MWth took place until 2005, when North Korean scientists opted to discharge the core after an average burnup of only 330 MWth-d/T.[47] This low-burnup spent core was reprocessed over in late 2005, yielding an estimated 10 - 14 kg WGPu. A third reactor core was loaded, and remained in residence until 2007, when it was discharged with an average burnup of less than 200 MWth-d/T. The spent fuel from this core was reprocessed in March of 2009 to yield roughly 8 kg of WGPu.

These estimates of Pu production are tallied in Table 4. They indicate that North Korea has likely produced and separated between 40 and 60 kg of WGPu throughout the history reactor operation at Yongbyon. It is believed that the first two tests, and possible the third test, utilized up to 6 kg of WG-Pu each. Hence, North Korea probably has between 24 and 42 kg of WGPu available today.

Table 4. Estimated Pu production at Yongbyon nuclear complex

Observed shutdown	*Residence; avg. burnup*	*Amount. spent fuel removed*	*Reprocess duration*	*Separated WGPu*	*Data/reasoning*
1989 (70-100 days)	3 years; unknown	Unkn.	Unknown	Less than 2 kg, possibly <100g	Satellite imagery; information of Calder Hall reactors (Albright et al. 2000)
1994 (unloaded in 36 days)	Unknown; ~650 MWth-d/t	Full core; 8,000 elem.; 50 t U	Jan.-June 2003	20 – 30 kg	IAEA statements on shutdown duration; Ri Hong Sop indication in 2004
2005 (~70 days)	2 years; 330 MWth-d/t	Full core; 8,000 elem; 50 t U	June-Dec. 2005	10 – 14 kg	Ri ind. 2004; satellite imagery for reactor operations
2007	1 year; <200 MWth-d/t	Full core; 8,000 elem; 50 t U	2009	~ 8 kg	Satellite imagery

9. Estimating HEU production.

In recent years, several authors have published estimates of HEU production in North Korea. The most widely cited study was conducted by David Albright.[48] Albright made

[47] As stated by Director Ri to S.S. Hecker during the 2006 Stanford delegation visit.

[48] David Albright, "Future Directions in the DPRK's Nuclear Weapons Program: Three Scenarios for 2020," U.S.-Korea Institute at SAIS, February 2015, http://38north.org/wp-content/uploads/2015/02/NKNF-Future-Directions-2020-Albright-0215.pdf

three estimates by assuming different levels of capability, with a high estimate of 48,000 – 58,000 kg-SWU/year by 2020. Bistline et al.[49] attempted to constrain uncertainty of the possible production rate by considering limited supply of critical materials required for centrifuge construction. Through expert elicitation, they predicted that supply of maraging steel, high-strength aluminum, and pivot bearings would be the main bottlenecks on the expansion of enrichment capacity. Bistline et al. utilized optimization and Monte Carlo tools to derive a probability distribution for enrichment capacity, which spanned a large range consistent with the uncertainties of DPRK capabilities. The mode, or most likely, capacity was estimated to be 35,000 kg-SWU/year by 2015. One of the authors of the current study, Braun, made two new estimates – the mechanistic and schedule-based approaches described in Appendix 2 – which predict 34,600 and 32,000 kg-SWU/year respectively. These estimates are summarized in Table 5.

Table 5. Summary of estimates for North Korea's enrichment capacity.

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

The above estimates of enrichment capacity can be utilized to derive an estimate for the stockpile of HEU potentially available for the weaponization program by 2015 or later. Such estimates are hampered by the tenuous nature of the overall enrichment capacity estimates. We know little about the actual installed capacity in North Korea except for the original UEW, as discussed above. We further don't know what portion of the

[49] Bistline et al. 2015. Op. cit.

enrichment capacity was dedicated to the fuel production for the ELWR and when (if at all) that capacity was modified to produce HEU for the weapons program.

There also exists the possibility that some enrichment capacity was dedicated to the production of enriched fuel for the IRT-2000 reactor to enhance its capability to produce medical isotopes or to undertake lithium targets irradiation for tritium production as discussed in Appendix 3 below. Thus, while enrichment capacity estimates are tenuous, plant utilization estimates are even more tenuous. Nevertheless, we provide the best estimate by the end of 2015 based on our understanding of the North Korean enrichment complex. We present three estimates: Albright et al. (October 2015), Braun (October 2015, See Appendix 2) and Hecker (based on Bistline et al, November 2015). The estimates are listed in Table 6 below.

Table 6: Estimates of Highly Enriched Uranium Stockpile in North Korea by 2015

Reference	**Enriched Uranium Stockpile** kg HEU 2015
Albright[50]	100 – 240 End of 2014 (1) 110 – 320 End of 2015 est.
Hecker (based on Bistline et al.[51])	300 End of 2015 (2)
Braun in Appendix 2 below.	75 – 100 End of 2015 (3)

(1) - Lower estimate is for Scenario 2: One enrichment plant operating.
Higher estimate is for Scenario 1: Two enrichment plants operating.

(2) - Based on maraging steel availability. Annual production capacity of 150 kg/year.

(3) - Lower estimate is based on mechanistic approach. Higher estimate is based on scheduler approach (See Appendix 2). Both estimates assume DPRK enrichment

[50] David Albright, "Future Directions in the DPRK's Nuclear Weapons Program: Three Scenarios for 2020," U.S.-Korea Institute at SAIS, February 2015, http://38north.org/wp-content/uploads/2015/02/NKNF-Future-Directions-2020-Albright-0215.pdf
[51] Bistline et al. 2015. Op. cit.

capacity dedicated to ELWR fuel production until the end of 2014, converted to HEU production starting 2015.

Summary

This report provides our best estimates of the current state of the nuclear facilities in the Yongbyon Nuclear Complex as of the end of 2015. We also provide our best estimates of the stockpile of fissile materials and the production capacity as of that time.

Appendix 1. Challenges in cooling the 5MWe and ELWR

After the destruction of the 5MWe reactor's cooling tower, and with the varied and shifting flow of the Kuryong river, cooling of both reactors appears to be one of the pressing challenges faced by Yongbyon engineers. This section addresses the question of secondary cooling for both reactors. In addition to the reactors, other facilities place demands on the river's water supply, such as the waste storage, reprocessing and other facilities

From overhead imagery it appears that the secondary cooling systems of both the. 5 MWe reactor and the ELWR have been combined and are both driven by the ELWR's pump house, located to the southeast of the ELWR building. The water pipes leading from the pump house to the ELWR's nuclear island building are laid in the vicinity of the previous location of the old cooling tower, and likely connects there to the 5MWe intake pipes.

Figure A.1 shows markings of all observed features -- including cisterns, trenches for piping, and the pump house -- that are believed to be associated with the combined cooling systems of both reactors. It is reasonable to assume that the ELWR will function like a typical pressurized-water reactor (PWR), which is illustrated in Fig. 7. In this case, a primary hot water system (under pressure to prevent boiling) and an intermediate water-steam system which removes heat from the steam generators at the reactor hall and pipe the steam to the turbine generator located in the turbine hall, just south of the reactor building. The intermediate water loop passes through the condenser below the turbine where the water flow is cooled with the secondary water flow, from the Kuryong River, driven by the pump house.

The first signs of the secondary cooling system were visible in May of 2011. Long trenches were seen extending out into the riverbed, from two cylindrical objects that appear to be cisterns to ensure consistent water intake. By September 2011, construction was visible on what would become the pump house, and trenches were seen connecting with the turbine and reactor halls of the ELWR. In March 2013, the trench that is likely associated with hot-water discharge -- extending from the turbine hall south to a location downstream from the water-intake locations -- was visible. The engineers appear to be testing the water flow for the secondary coolant system on June 9, 2013, as there is a white plume where the end of the discharge pipe is believed to be located. This is the only image in which discharge water appears. Future visibility of discharge may provide a signature to indicate reactor operation. Evidently the ELWR's pump house was completed in the second half of 2013 and it is then that the 5 MWe reactor which has been dormant since 2007 and since the destruction of the cooling tower in 2008, started working again. This is additional indirect evidence that the cooling systems of both reactors were coupled through the operation of the ELWR's pump house.

Fig. A.1. Location of all observed features related to the secondary cooling systems of the 5MWe GCR and the 25-30MWe ELWR (image from Google Earth, 10/27/2014, CR 2015 DigitalGlobe).

Before the old cooling tower was destroyed in 2008, the reactor was cooled using a closed loop cooling system between the turbine hall and the cooling tower. The hot CO_2 gas from the 5MWe reactor (~20MWth) was cooled by passage through a large vertical heat exchanger (referred to as the boiler) against a water stream in an intermediate cooling water loop. The steam exiting the boiler was piped out of the reactor building into the turbine hall. It then would pass through the turbine and its condenser and exchanges heat against the external-cooling-loop water stream flowing through the condenser's tubes. The primary cooling water was then returned in a closed loop to the reactor building again. The heated external cooling system water was piped into the cooling tower and cooled against air, at which point a portion of the water would evaporate and carry off a substantial portion of thermal energy. This evaporated water loss would be replenished by an external make-up water supply from the river through an external pipe due east from a location just north of the cooling tower. That make-up water pipe ended in a cistern located in the river east of the cooling tower location.

With the cooling tower gone by June 2008, the old external cooling system had to be changed from a closed-loop system, with an additional make-up water supply, to a once through system. Cold river water must now be supplied to the external cooling system at one or more points, and passes through the turbine's condenser only once before being returned to the river. Since the observed trenching from the pump house passes through the location of the old cooling tower, it is believed that the connection is there. However, without the evaporative heat loss, more water is now required to achieve the same rate of cooling. It is possible that some water is also drawn from the original cistern for the existing make-up water pipe as well. A new discharge pipeline, exiting the turbine hall of the 5MWe reactor and proceeding due east straight to the river was also observed, and a discharge plume has been observed intermittently since 2013, indicating sporadic reactor operation. While the location of the discharge upstream of the intake locations is unusual, this may be a temporary solution, and it may also be that the separation is sufficient to prevent mixing hot discharge into the cold-water intake. The ELWR pump house now becomes a common mode failure risk, i.e. failure of operation of the pump house will now affect the operation of both reactors.

With the increased demand for water from the river, there seems to have been some difficulty ensuring consistent water flow to both reactors. This difficulty is exacerbated by the changing river conditions, such as freezing, silting around bends, and changes in the river landscape during floods. On some occasions, the intake cisterns have been filled with sand. In order to address this, DPRK engineers constructed an earthen dam in early March 2014 just south of the ELWR so that the large water pool trapped north of the dam may provide improved intake water supply to both reactors. The dam is located just upstream from the (apparent) discharge pipe for the ELWR so that hot water from the larger reactor will not mix with the trapped cooler water. A gate was also installed in order to regulate the amount of trapped water. The earthen dam and gate were breached during heavy rains pour in 2014 and have been repaired since. Nevertheless, the dam and gate represent another common mode failure mechanism in that if significantly breached this would threatened the adequate cooling water supply source for both reactors. The combined effect of these issues raises the concern of common-mode failures and inadequate water supply for full power operation of both reactors.

Appendix 2. Estimating uranium enrichment capacity in North Korea (C. Braun)

The purpose of this appendix is to provide an estimate of the potential for highly enriched uranium (HEU) production in the North Korea based on the data available on existing and putative enrichment plants in North Korea. Pyongyang chose to publicize its enrichment capabilities by inviting the Stanford University delegation to visit a newly constructed centrifuge plant housing 2,000 P-2 type centrifuges, at the Yongbyon Nuclear Scientific Research Center in November 2010.[52] The visit of the Stanford delegation is the only time outsiders have seen a North Korean Uranium Enrichment Workshop (UEW) from the inside. All other information about enrichment in North Korea is based on overhead imagery and on various assumptions as detailed below.

In the body of this paper, we reference the work of the Stanford team of Bistline et al. who took a probabilistic approach to estimating the centrifuge capacity based on the likelihood of North Korea importing requisite critical materials or being able to produce such materials indigenously. In this appendix, I describe two additional methods to estimate the enrichment capacity. Two methods are developed: a mechanistic approach based on ad-hoc assumptions, which I consider reasonable and a schedule-based approach related to the possible schedule of construction of enrichment facilities in North Korea. I refer to the second method as a schedular approach. Both methods are based on the assumptions that North Korea is not constrained in centrifuges manufacturing and installation by equipment, production capacity or trained personnel availability.

The two estimation methods are used first to estimate the prospective total enrichment capacity installed in North Korea, and then to estimate the possible HEU production rate from the assumed enrichment complex.

In applying the two methods it is important to specify what we know of North Korean enrichment complex before embarking on further assumptions. Construction and installation took only one and one half years even for this first-of-a-kind plant. This enrichment plant contains 2,000 centrifuges arrayed in six cascades of ~330 centrifuges per cascade, representing a total enrichment capacity of 8,000 SWU/Year. Each P-2 type centrifuge has a separative capacity of 4 SWU/Year per machine as reported by North Korean engineers. This capacity could produce annually up to 40 kilograms of HEU (90 % enriched at 0.25% tails assay), or two tons of 3.5% low enriched uranium (LEU) (at 0.25% tails assay). The ELWR is estimated to have a full core load of 4 MT of LEU and an annual refueling requirement of ~ 2 MT LEU per year.

Overhead imagery indicates that between April 2013 and November 2014 North Korea doubled the size of its enrichment plant building. There was a wait period of more than two years between the end of construction of the first enrichment module of the UEW and the start of construction of the second. These are all the known facts of this case. Everything else is assumption.

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[52] Siegfried Hecker, John W. Lewis, Robert Carlin, "Report of Visit to Yongbyon Nuclear Scientific Research Center" Trip Report of Stanford Delegation, Stanford, CA, November 12, 2010. Available at: http://iis-db.stanford.edu/pubs/23035/HeckerYongbyon.pdf

The first basic assumption made here is that production capacity of the UEW probably doubled when the building size doubled, to 4,000 centrifuges with separative capacity of 16,000 SWU/Year.. We assume that the on-site construction and installation of the second enrichment module of 2,000 centrifuges took also one and one half years. In general, a portion of the centrifuges manufacturing period could overlap with the on-site construction and equipment installation period of the enrichment plant.

The second basic assumption made here relates to the existence of a pilot plant, located elsewhere, which served as the basis for the construction of the Yongbyon UEW. I assume that such plant had a capacity of up two cascades of the type seen in Yongbyon, i.e. two cascades of 330 centrifuges each or about 2,640 SWU/Year. This size facility would be the minimum required to study both intra-cascade and inter-cascade operations. It is unlikely that North Korea had managed to build its first enrichment plant in Yongbyon without relying on design and construction data obtained during the installation and operation of the pilot plant.

The third basic assumption made here is that North Korea has embarked on the construction and operation of a clandestine enrichment plant of a size about similar to the UEW. While the Yongbyon plant might be producing only LEU to provide fuel for the prospective ELWR, the clandestine plant could be dedicated to producing HEU for weapons purposes. The clandestine enrichment plant could use as feed either the LEU produced in the UEW at Yongbyon, in which case it would operate as a 'topping' plant, as discussed below, or it could use a natural uranium feed and enrich it all the way to HEU.

I further assume that all the fuel cycle facilities supporting the operation of the enrichment complex exist and do not constrain enrichment operations.

With these assumptions in mind it is possible to estimate the total enrichment capacity in North Korea by the two methods, mechanistic and schedular.

A.2.1. Mechanistic approach to enrichment capacity estimation

In the mechanistic approach we postulated that the clandestine operating capacity must equal the 'open' or acknowledged capacity. This is so since if North Korea through some future agreement within the six-parties framework might declare its acknowledged enrichment plant to the IAEA and place it under safeguards, it will still need an equal enrichment capacity at a clandestine site to be used as a HEU production hedge. Based on this logic we estimated a total enrichment capacity of:

- Pilot plant – 660 centrifuges ~ 2,640 SWU/year capacity
- Yongbyon plant – 4,000 centrifuges – 16,000 SWU/year capacity
- Clandestine plant – 4,000 centrifuges – 16,000 SWU/year capacity
- Approximate Total DPRK enrichment capacity ~ 8,700 Centrifuges – 34,640 SWU/year

We further assumed that all this centrifuge capacity would be available by 2017.

A.2.2. Schedular approach to enrichment capacity estimation

The known enrichment capacity build-up data indicate that North Korea has managed to manufacture a sufficient number of new centrifuges to construct and install a new enrichment plant of ~ 2,000 centrifuges every 1.5 to 2.0 years (2009-2010 for the original UEW, and we assume 2013-2014 for the expansion plant. It is likely that North Korea has an industrial base sufficient to produce an even larger number of centrifuges per year, however only a portion of its industrial base is dedicated for the production and installation of 2,000 centrifuges every approximately 1.5 years.

It is possible to estimate (though no proof exists) a construction time-scale for such centrifuges module as follows:

1. North Korea has two imported flow-forming machines with known manufacturing capacities of 1,000 and 500 P-2 type rotors per year. This capacity should suffice for the production of 2,000 centrifuges every one and one half years.
2. The production of all other centrifuge components is not on the critical time path

It is thus possible that with the completion of the first part (or module) of the Yongbyon UEW (2,000 centrifuges) by late 2010, North Korea might have started the construction of a clandestine enrichment facility of equal size (about 2,000 centrifuges) at a clandestine site, and this required also about two years (2011 – 2013). I assume that North Korea might install enrichment capacity in modules of 2,000 centrifuges each since three such modules are required to operate in an integrated–cascades mode as discussed below.

With the possible completion of such clandestine enrichment facility North Korea must have turned to the expansion of the UEW in Yongbyon (2,000 additional centrifuges) – an additional enrichment module installed over the 2013-2014 period. Otherwise it is not clear why the construction of the Yongbyon enrichment expansion module had to wait from 2011 to 2013. Thus if one accepts such construction schedule assumption then North Korea has by 2015 a 6,000 centrifuges enrichment complex divided into a base facility of 4,000 centrifuges in Yongbyon producing LEU (UEW and UEW expansion modules of 2,000 centrifuges each) and a clandestine ‘topping' plant of 2,000 centrifuges located elsewhere. The topping plant might be fed with the Yongbyon product LEU and convert it to HEU, as described next.

It is further possible that with the completion of the expanded UEW at Yongbyon North Korea could embark in 2015 on the construction of a new expansion module of the clandestine site, to consist also of 2,000 centrifuges. Such plant could be completed in late 2016 or 2017. This implies that by 2017 North Korea could have 4,000 operating centrifuges (in two modules) in Yongbyon and potentially another 4,000 operating centrifuges (in two modules) at a clandestine site. Thus both the mechanistic and schedular approaches lead to a similar estimate of total installed enrichment capacity in North Korea by 2017. While the mechanistic approach assumes a-priori a clandestine enrichment plant of similar capacity to the Yongbyon plant, the schedular method adds a possible time line for the activation of such total enrichment complex. A hypothetical schedule for the construction and installation of uranium enrichment facilities in North Korea, based on the above discussion, is shown in Figure A.2.1.

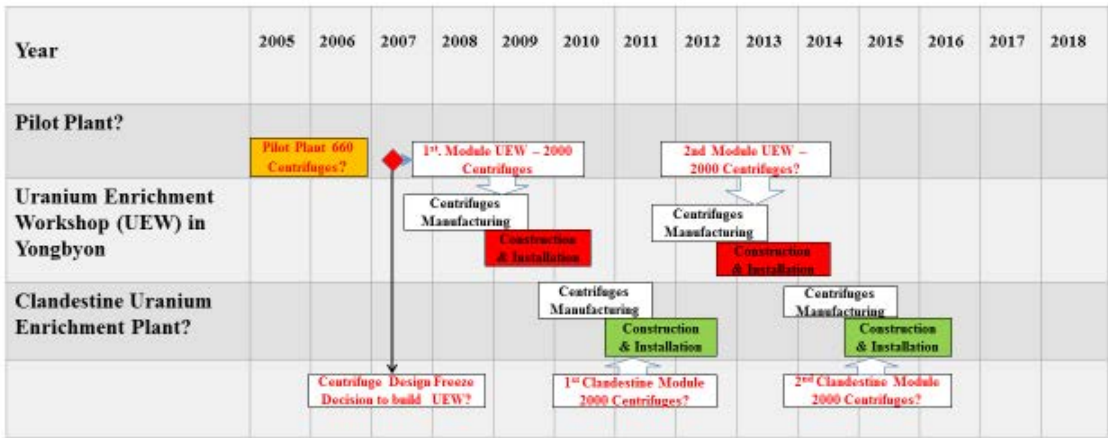

Fig. A.2.1. Hypothetical Construction Schedule of Enrichment Facilities in North Korea

As seen in Fig. A.2.1, the decision to freeze the centrifuges design and proceed with manufacturing and with the construction and installation of the Yongbyon Uranium Enrichment Workshop must have been taken sometime in the second half of 2007, and no later than the first quarter of 2008, as discussed above, to allow for centrifuges manufacturing and for the startup of the on-site construction in Yongbyon by March 2009.

The fourth enrichment module of 2,000 centrifuges if indeed installed during the 2015-2016 period would improve North Korea's flexibility, allowing it to dedicate three of the four enrichment modules to HEU production while dedicating the fourth module to the LEU enrichment requirements of the ELWR, once it starts operating.

A.2.3. Estimating prospective HEU production capability in North Korea

Given the above enrichment capacity estimates, we estimate the amounts of HEU this size enrichment complex might produce.

Mechanistic estimate - Using the mechanistic approach we note that a 2,000 P-2 type centrifuges plant could produce up to 40 kilograms of HEU per year if properly configured, as discussed above. Thus a 4,000 centrifuges plant such as the expanded UEW by 2015 could produce ~ 75 kilograms of HEU per year or the equivalent of three bombs worth per year. Likewise the postulated expanded clandestine enrichment plant by 2017 (4,000 centrifuges) could also produce ~ 75 Kilograms of HEU per year, if configured that way. I assume here that the Yongbyon UEW produced LEU for the ELWR from 2011 till 2015. By 2015 it must have produced the first core load and two annual reloads of LEU, and then converted in 2015 to HEU production. The clandestine enrichment plant coming fully on line by 2017 might likely be configured from the outset for HEU production. The total HEU production potential, assuming no enrichment work assigned to ELWR reloads after 2015, could be:

- 75 Kilograms per year during 2015-2016 from the expanded Yongbyon UEW (two enrichment modules).
- 150 kilograms per year from 2017 and thereafter from the two Yongbyon and the two clandestine enrichment modules.

Schedular estimate - The starting point for this analysis is the Pakistani configuration for an interconnected-cascades enrichment plant proposed by the A. Q. Khan network for the prospective Libyan enrichment plant.[53] This scheme was transferred to the South African contractors of the Khan's network for the manufacturing of the plant's piping system and later came to light. According to data provided by Glaser, (see Figure A.2.2 below) a 4,000 centrifuges enrichment plant (base plant) producing 3.5% U-235 LEU product would require an additional ~ 1,900 centrifuges topping plant, divided into three separate sections, to produce the requisite 90% enriched HEU.

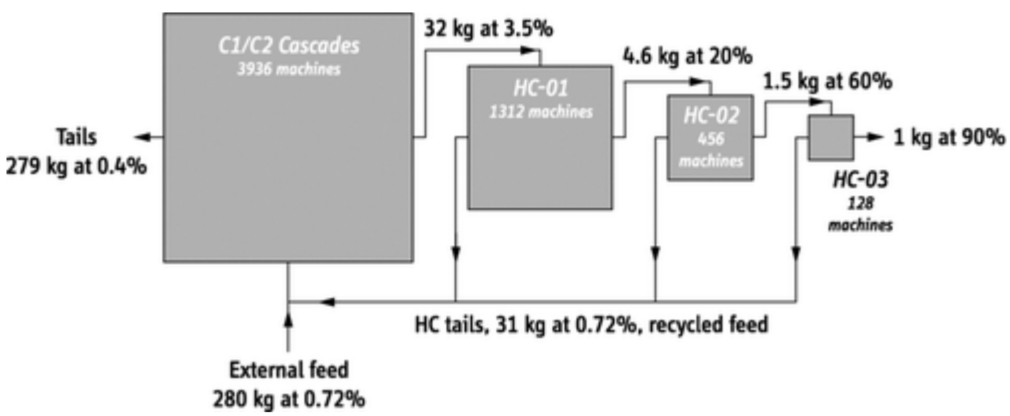

Fig. A.2.2. Interconnected-cascades Enrichment Plant Configuration proposed for Libyan Enrichment Project (Normalized)

Each section of the interconnected-cascades plant requires approximately one third of the number of centrifuges used in the previous section, as follows:

- 4,000 centrifuges LEU base plant with natural uranium feed produces 3.5% enriched U-235 (tails assay – 0.4%).

[53] A discussion of a possible interconnected cascades configuration is discussed in: Alexander Glaser, "Characteristics of the Gas Centrifuge for Uranium Enrichment and Their Relevance for Nuclear Weapon Proliferation (Corrected)" See Figure 8 and Table 4, pp.18-20, Paper published in Science and Global Security Journal Vol. 16, pp.1-25, 2008. Available at: http://scienceandglobalsecurity.org/archive/2008/10/characteristics_of_the_gas_cen.html

- 1,320 centrifuges 1st stage topping plant with 3.5% feed produces 20% enriched U-235 (0.71% tails)
- 460 centrifuges 2nd stage topping plant with 20% feed produces 60% enriched U-235 (0.71% tails)
- 130 centrifuges 3rd stage topping plant with 60% feed produces 90% enriched U-235 (HEU) at 0.71% tails assay.

All tail streams from the three topping plant stages might be recycled back to the LEU plant's feed stream to reduce external feed supply

As this example indicates the 4,000 centrifuges expanded UEW at Yongbyon operating as a LEU enrichment plant only will require an interconnected-cascades topping plant of 1,900 centrifuges to convert its output into weapons grade HEU. This configuration of the interconnected-cascades might explain the schedular approach to enrichment complex modular construction discussed above. The LEU produced in the base enrichment plant at Yongbyon is taken to the clandestine topping enrichment plant where it is converted to HEU. Thus the schedular enrichment capacity expansion schedule estimate meshes with the interconnected-cascades configuration employed by A.Q. Khan, to possibly explain North Korea's approach to the enrichment complex expansion.

Documents on enrichment plant design provided by the A.Q. Khan network to the Libyans and to their South African sub-contractors further indicate that a 5,900 centrifuges plant of the interconnected-cascades configuration mentioned above, using P-2 type centrifuges (the type provided to Libya) could produce 100 kilogram of weapons grade uranium per year.[54] It also follows that a half-sized enrichment plant utilizing 3,000 P-2 type centrifuges might be able to produce about 50 kilograms of HEU on an annual basis.

Given the above we could estimate that by 2015 North Korea might have a three-module 6,000 centrifuges enrichment complex in operation (two base modules producing LEU in Yongbyon and a topping module taking the LEU feed and producing HEU). This complex could produce 100 kilograms of HEU per year per the Pakistani estimates reported by Albright. In addition North Korea might have by 2017 an additional 2,000 centrifuges enrichment module at its expanded clandestine site and additional enrichment capacity in the pilot plant. The second clandestine module at the pilot enrichment plant operating in tandem with the pilot plant, and representing half of the A.Q. Khan's enrichment plant configuration could produce an additional HEU amount of about 30 - 50 kilograms of HEU per year, if configured to do so. Thus the maximum HEU production capability of North Korea by 2017 based on the schedular capacity expansion approach and the Pakistani interconnected-cascades design is estimated as ~ 130 – 150 kilograms per year. This is similar to the mechanistic approach estimate of 150 kilograms per year discussed above. The total HEU production rate could be 100 kilograms per year during 2015 – 2016 from the two Yongbyon enrichment modules and the clandestine module (6,000 centrifuges) operating in an integrated-cascades mode; ~ 130 – 150 kilograms per

[54] David Albright, "North Korea Plutonium and Weapons Grade Uranium Inventories", ISIS Report, Washington DC, Revised October 5, 2015, Available at: http://www.isis-online.org/uploads/isis-reports/documents/North_Korean_Fissile_Material_Stocks_Jan_30_2015_revised_Oct_5_2015-Final.pdf

year from 2017 and thereafter, the extra 30-50 kilograms obtained from the integrated operation mode of the second clandestine enrichment module and the pilot plant (2,640 centrifuges).

Appendix 3. Possible tritium production in Yongbyon

As of December 2015, North Korea has conducted three nuclear tests thus far and is threatening to conduct a thermonuclear weapon test. This raises the issue of how and where might tritium be produced for North Korea's nuclear weapons program, either for boosted fission weapons or thermonuclear weapons. We believe that tritium production is likely performed in the Yongbyon nuclear center, as that center handles most radiochemical work. North Korea will need to master the technologies of Li-6 enrichment, and of tritium separation from irradiated lithium targets, in order to provide the requisite tritium for the weapons program. The United States and the Soviet Union mastered these technologies during the 1950's and so it would not be surprising if North Korea has acquired some degree of proficiency in these technologies during the past five years. We propose the following sequence of steps for North Korea to produce tritium in Yongbyon:

1. Irradiation of lithium targets

Neutron irradiation of Li-6 targets produces tritium and helium to recover the tritium. Currently there are two operating reactors in the Yongbyon nuclear center: The IRT-2000 and the 5MWe reactor, both discussed above in this report. The third reactor in the Yongbyon center, the ELWR, is not yet operational.

The IRT-2000 uses HEU fuel provided by the Soviet Union prior to 1991, as discussed above. The IRT-2000 is mostly used for medical isotopes production and is operated only sporadically in order to conserve the original fuel. When the need for new medical isotopes arises the reactor is operated for only a few days at a time. This mode of operation is not suitable for tritium production, which requires continued irradiation for several months (or years) depending on the amount of tritium required. Thus, should North Korea wish to employ the IRT-2000 reactor for lithium targets irradiation it would have to domestically produce new HEU fuel elements. The IRT-2000 contains several irradiation tubes passing through the center of the reactor where lithium targets could be inserted. This option would produce only limited amounts of tritium considering the small size of the IRT-2000 reactor and the limited capacity of the irradiation tubes.

In order to use the IRT-2000 reactor with newly manufactured fuel elements, a portion of the enrichment complex in Yongbyon (and elsewhere) would need to be reconfigured to produce the requisite enrichment of the HEU. North Korea would also need to master the technology of Russian fuel elements manufacture, at sufficient degree of reliability for the safe operation of the IRT-2000 reactor. Both the enrichment and fabrication technologies are within North Korea's range of capabilities though they might lack experience in manufacturing leak-tight high reliability fuel elements. Assuming North Korea could produce the requisite HEU fuel elements for the tritium production mission, they would still be sacrificing some HEU enrichment potential that could have been dedicated for weapons-grade HEU enrichment for their military program.

The other option available is to irradiate lithium targets in the 5MWe reactor. This could be done in one of two ways. The lithium targets could be inserted in standard vertical fuel element channels and removed when the lithium is considered sufficiently irradiated. The other option would be to construct new dedicated irradiation tubes from outside reaching the center of the reactor's core and placing the lithium targets only in the irradiation tube(s). While the second option is feasible, it will limit the number of lithium targets that could be irradiated at any time. Regardless of the irradiation method chosen there is also a trade-off inherent in this tritium production method. The neutrons absorbed in the lithium targets are thus not available for plutonium production, which[55] is the main mission of the 5MWe reactor.

In September 2014 and September 2015 there appeared isolated reports of increased activity at the RCL based on analysis of satellite imagery. A shielded truck carrying spent fuel elements from the 5MWe reactor's spent-fuel pool was seen near the reprocessing center. This led to speculation that a partial de-fueling of the 5MWe reactor might have occurred and that possibly defective fuel elements were removed for reprocessing even prior to the reactor's planned refueling time (which has not occurred yet). Considering the emergence of the tritium issue, it is now possible to speculate that the fuel elements incorporating lithium targets might have been removed on these very occasions and that the lithium targets were then sent to the processing facility. This hypothesis is based on several un-provable assumptions, however the timing is right given North Korea's claims of thermonuclear weapons potential.

2) Tritium extraction

Two potential sites exist in the Yongbyon nuclear center that could be used for processing irradiated lithium targets for tritium extraction. First, the existing hot cells in the isotopes production laboratory (IPL) located near the IRT-2000 reactor at the northern (older) part of the Yongbyon reactors complex (west side of the Kuryong River). Or, second, a potentially new hot cell facility now under construction at the southeastern part of the FFP (see Figure 8 above). The large RCL is likely not used for tritium extraction since it is dedicated to plutonium extraction from the highly radioactive spent fuel using the PUREX process as explained above.

The IPL facility near the IRT-2000 reactor was constructed concurrently with the reactor and complemented its function as producer of medical isotopes. Over the years, various targets were irradiated in the reactor and then separated, cleaned, and packaged at the

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[55] W. Mugford, J. Liu, "North Korea's Yongbyon Nuclear Facility: New Activity at the Plutonium Production Complex." A 38North Satellite Imagery Analysis, September 8, 2015. Available at: http://38north.org/2015/09/yongbyon090815/
Also, N. Hansen, "North Korea's Yongbyon Nuclear Facility: Reactor Shutdown Continues; Activity at Reprocessing Facility." A 38North Satellite Imagery Analysis, November 19, 2014. Available at: http://38north.org/2014/11/yongbyon111914/

nearby hot cell facility. The IPL has been used for various radiochemical separations for several decades although it operated only sporadically because of the need to conserve the HEU fuel, which was in short supply. The operating staff at the IPL is likely very familiar with the requisite radiochemical separations procedures and processes.

A new facility has been observed in satellite imagery to be under construction at the southeastern corner of the FFP in the Yongbyon nuclear center, near the railroad yard[56]. This facility was seen during its construction stages in 2014 to contain what looked like five hot cells arranged in a row, facing a large operating floor. The facility was covered with a roof in 2015 and it has been impossible since to learn more regarding its mission or the progress made in its completion. A tall stack seen near the facility could serve for discharging non-condensable (presumably radioactive) gases from chemical separation operations to the atmosphere. It is difficult to estimate when the interior work on this facility will be completed and when will it start operations. The available imagery also does not provide any information on what kind of operations are planned for this facility once it is completed. The hot cells appear to have less concrete shielding than the radiochemical laboratory. They are also smaller and appear more suitable for processing irradiated targets rather than for processing of highly radioactive spent-fuel elements. Therefore, it appears that the new hot cells facility might be used as a modern dedicated tritium production facility.

Appendix 4. Decision analysis tools for nuclear facility disposition

As a part of the analysis of the nuclear energy center in Yongbyon and the potential for its dismantlement we started developing decision analysis tools to support rational decision-making regarding the prospective disposition of various facilities in the center. This project aims to address the intricacies inherent in evaluating the current status and potential uses of North Korea's nuclear infrastructure. Specifically, the wide range of buildings of differing types and functions that comprise the Yongbyon Nuclear Scientific Research Center, their interdependence, as well as their varying economic, political and technical values, all inform the development of an integrated decision analysis framework. Such modeling tool would apply universal criteria in order to optimize the decisions regarding the disposition of various facilities in this legacy infrastructure. The decision analysis tool proposed below employs a multi-faceted approach that combines the analysis of both qualitative and quantitative factors that are key in determining the prospective optimum utilization or dismantlement of North Korea's Yongbyon nuclear center under a prospective Korean peninsula unification scenario. In this section we review the early development work on this modeling tool conducted so far. We hope to complete this modeling tool and apply it to sample facilities in the Yongbyon nuclear center to better demonstrate its usefulness.

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[56] W. Mugford, "North Korea's Yongbyon Nuclear Facility: Sporadic Operations at the 5 MWe Reactor But Construction Elsewhere Moves Forward." A 38North Satellite Imagery Analysis, July 24, 2015. Available at: http://38north.org/2015/07/yongbyon072415/
Also, David Albright and Serena Kelleher-Vergantini, "Update on North Korea's Yongbyon Nuclear Site" ISIS Report, Washington DC, September 15, 2015. Available at: http://isis-online.org/uploads/isis-reports/documents/Update_on_North_Koreas_Yongbyon_Nuclear_Site_September15_2015_Final.pdf

A.3.1. Methodology

The assessment of a highly complicated, valuable and potentially dangerous nuclear complex requires a multilayered evaluation capable of taking into consideration a wide spectrum of factors. By analyzing the potential value that a facility within the Yongbyon nuclear infrastructure may possess, as well as the threats it may pose, we could identify six principal criteria that will constitute the basis for the possible disposition decision; The factors we chose are:

- Nuclear Proliferation danger: The potential for the diversion of nuclear material, equipment, technology/knowhow or personnel.
- Impact on the local economy: The potential impact that each specific nuclear-related facility might have on its surrounding economic ecosystem, which might include both direct (on site) and indirect labor (jobs created through the surrounding communities and other enterprises providing miscellaneous support services to the specific facility).
- Impact on overall North Korean economy: The potential impact that each specific nuclear facility might have on the economic prospects of the future North Korea.
- Impact of the specific nuclear facility on the entire Korean peninsula: The potential ways through which a specific nuclear facility in North Korea could be integrated into the South Korea nuclear infrastructure, thus assuming an ancillary role in a unified Korean nuclear system post-unification.
- Short-term environmental impact: The potential threat to the environment that a specific damaged or poorly maintained nuclear facility might pose if not immediately disposed of.
- Long-term environmental impact: The potential threat to the environment in case of long-term decommissioning operation and storage/disposition of the resulting radioactive waste.

A.3.2. Decision analysis model description

The decision criteria listed above have been incorporated in a decision analysis model that aims to identify the optimum combination of facility disposition decisions within a nuclear complex such as Yongbyon, which might maximize the prospective economic values while minimizing risks related to prospective nuclear proliferation or possible environmental damages. It should be noted that the model could provide decision makers with substantial autonomy in parameterizing its application thus allowing them to select different subsets of criteria as the basis for partial optimizations. The decision analysis model consists of a decision tree that is applicable to analyzing the disposition decisions with respect to either a single specific facility separately, or a combined subset of interrelated facilities. We intend to apply the decision analysis model initially to specific sample buildings and subsequently to a group of facilities of interrelated function. Ultimately, by identifying a subset of facilities within the nuclear center that might yield the highest benefit or minimum damage cost for the model aims to provide a framework for informed decision-making.

According to the model each nuclear facility can have three different possible disposition options:

- Preservation, refers to maintaining the building in its current status for future beneficial use
- Modification, refers to modifying the operation/function of the building to conditionally allow future operation
- Dismantlement (or demolition), refers to the process of dismantling the building

Moreover, for each principal criterion the decision model encompasses three different scenarios; namely baseline, optimistic, and negative. The decision tree follows the structure illustrated in Table 12.

The first 3 branches indicate the three available decisions regarding the status of each building (i.e. preserved, modified, or demolished). Also, the tree is vertically segmented into 6 zones, each representing a single principal criterion. As we move towards the right, three branches are generated each time we enter a new criteria zone accounting for the baseline, optimistic, and negative scenario. Through this comprehensive branching process the decision analysis model is capable of accounting for all different combinations of scenarios (i.e. baseline, optimistic, negative) under each initial decision (i.e. preserved, modified, demolished). For example, the user might be interested in the expected value of the decision to preserve building 1 when the optimistic scenario materializes in criteria 2 and 3 (local economy, national economy), the baseline scenario materializes in criteria 4, 5, and 6 (impact on Korean peninsula nuclear infrastructure, short term environmental impact, long-term environmental impact) whereas the negative scenario materializes in criterion 1 (nuclear proliferation). Also, the user might be able to acquire a high level overview of total expected value of each initial decision by factoring all possible scenarios of each criterion.

As shown above, the decision analysis model evaluates, in an integrated manner, factors that are amenable to quantification (e.g. impact on the local and national economy), as well as factors for which it is difficult to assign a specific quantity or value (e.g. proliferation impacts). Therefore, we decided to utilize monetary values as a universal metric in the decision analysis model and express the impact of each criterion in monetary terms, inasmuch as we are able to specify monetary values throughout.

A.3.4. Possible future roadmap activities

In the future phase of our project we aims to proceed along the following course of action in order to gather the necessary data that will constitute the input of the model, test the proposed decision analysis model, and apply in in sample analyses.

Cost/Benefit Assignment: The division of each criterion into three scenarios (i.e. baseline, optimistic, negative) creates the need to granularly identify the aspects and elements that characterize each scenario. For example, in the case of the optimistic scenario, for the local economy criterion, we would have to assume a possible number of jobs created, possible salaries for the employed personnel and potential increase of revenue for local communities, etc.

Probability Assignment: By working closely with Stanford University staff members experienced in nuclear infrastructure issues and the utilizing the resources that the University has to offer, we aim to assign probabilities for each scenario of each principal criterion.

Quantification of Criteria: As mentioned above, not all criteria are easily quantifiable. Therefore, we aim to establish a correlation between monetary values and the criteria in the decision analysis model that are not easily quantifiable (i.e. environmental impact and nuclear proliferation).

Pilot Testing: By applying the proposed decision analysis model on data sets deriving from historical cases where similar nuclear infrastructure underwent renovation, decommissioning, or functional transformation, we aim to conduct a potential retrospective validation of the proposed model and generate insights useful for making necessary enhancements to the model prior to its roll out.

Roll Out: After validating the proposed model, we aim to proceed to its implementation as related to specific sample facilities within Yongbyon nuclear center.

Fig. A.4.1. Decision analysis framework.