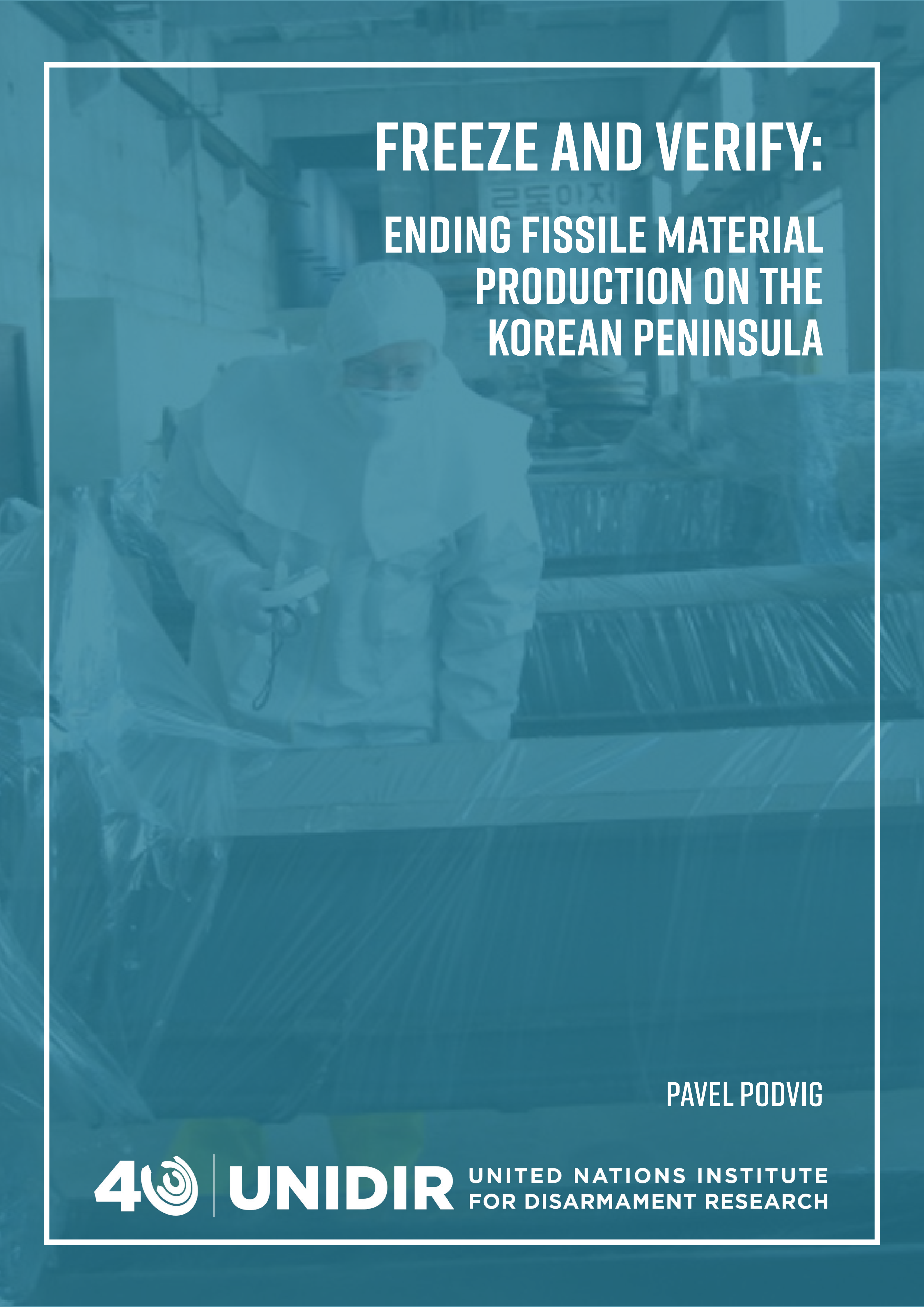

FREEZE AND VERIFY:

ENDING FISSILE MATERIAL PRODUCTION ON THE KOREAN PENINSULA

PAVEL PODVIG

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ABBREVIATIONS AND ACRONYMS

IAEA	International Atomic Energy Agency
HEU	highly enriched uranium
ELWR	Experimental Light-Water Reactor
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
SWU	separative work unit
MWe	Megawatt electric
MWt	Megawatt thermal

SUMMARY

1. Progress towards denuclearization of the Korean Peninsula critically depends on finding a way to constrain and roll back the nuclear programme of the Democratic People's Republic of Korea. A freeze on its fissile material production would be the first essential step in that direction, provided that it can be made effectively verifiable.
2. The arrangement for a verified freeze of fissile material production suggested here would create a mechanism to verify the suspension of all production activities. While production facilities would be declared and placed under monitoring to ensure their shutdown, the verification programme would not require a comprehensive declaration of all nuclear activities or access to fissile materials in military use. Verifying the absence of undeclared production facilities would rely on a declaration of the total amount of produced fissile materials.
3. The verified freeze arrangement would provide an opportunity to start verification at the early stages of the denuclearization process. It would provide a mechanism for building confidence and trust, which should make it possible to strengthen and expand the verification programme. It will eventually include military materials as well, although the removal of fissile materials from military use would be deferred to the time when the political normalization process makes it possible. In the end, the freeze verification arrangement would ensure that all material, military as well as civilian, will be accounted for and placed under appropriate safeguards.

INTRODUCTION

Achieving a non-nuclear Korean Peninsula has been one of the most difficult challenges for international diplomacy for almost thirty years. The elimination of nuclear weapons on the peninsula is an essential element of ending one of the oldest conflicts of the Cold War and ensuring peace and security in the region. The issue, however, is broader than regional security as it involves States outside of the region. Importantly, successful denuclearization of the peninsula would strengthen the nuclear non-proliferation norm and provide an invaluable model for future nuclear disarmament efforts.

The Republic of Korea and the Democratic People's Republic of Korea first expressed their commitment to denuclearization in a Joint Declaration of the Denuclearization of the Korean Peninsula signed in 1992.[1] As both States were parties to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) at the time, the declaration confirmed their obligations not to possess or develop nuclear weapons and to use nuclear energy solely for peaceful purposes. As a way to strengthen these obligations, the two States pledged not to possess reprocessing or enrichment facilities.

The Republic of Korea has upheld its commitment to the goals of the declaration. As a party to the NPT in good standing, it placed all its nuclear activities under safeguards and strengthened these safeguards by signing an additional protocol, which entered into force in 2004.[2] After conducting the required assessment, the International Atomic Energy Agency (IAEA) concluded that all nuclear material in the Republic of Korea remained in peaceful activities.[3] In addition to its NPT obligations, the Republic of Korea refrained from deploying uranium enrichment and reprocessing facilities in its peaceful nuclear programme. In addition, all US nuclear weapons, which were stationed in the Republic of Korea from the late 1950s, were withdrawn from its territory in 1991, before the 1992 declaration was signed.[4]

For its part, the Democratic People's Republic of Korea breached the central obligation of the declaration as it withdrew from the NPT, produced fissile materials for weapons, conducted a series of nuclear tests, and created an arsenal of nuclear weapons and delivery systems.

While the international community has undertaken several diplomatic efforts to constrain and roll back the Democratic People's Republic of Korea's nuclear weapons programme, ultimately none were successful. The history of these attempts contributed to the atmosphere of deep mistrust between the Democratic People's Republic of Korea and its counterparts which significantly complicates efforts to achieve progress toward denuclearization.[5] Moreover, today's

1 "Joint Declaration of the Denuclearization of the Korean Peninsula", 20 January 1992, https://peacemaker.un.org/sites/peacemaker.un.org/files/KR%20KP_920120_JointDeclarationDenuclearizationKoreanPeninsula.pdf.

2 When the Republic of Korea began implementation of the additional protocol, it disclosed some past experiments with reprocessing and enrichment. The IAEA, while expressing concerns about these activities, did not consider them to be a case of non-compliance with safeguard obligations. "South Korea", Nuclear Threat Initiative, December 2015, https://www.nti.org/learn/countries/south-korea/nuclear/; Olli Heinonen, *IAEA Mechanisms to Ensure Compliance with NPT Safeguards*, UNIDIR 2020, p. 21, https://doi.org/10.37559/WMD/19/WMDCE2.

3 That assessment, also referred to as a broader conclusion, was for the first time reached in 2007 and then confirmed each following year; "Safeguards Statement for 2007", IAEA, 2008, https://www.iaea.org/sites/default/files/es2007.pdf.

4 Hans M. Kristensen and Robert S. Norris, "A History of US Nuclear Weapons in South Korea", *Bulletin of the Atomic Scientists*, vol. 73, no. 6, 2017, pp. 349–357, https://doi.org/10.1080/00963402.2017.1388656. In 2005, the United States and the Republic of Korea formally confirmed the withdrawal; "Joint Statement of the Fourth Round of the Six-Party Talks", US Department of State, 19 September 2005, https://2001-2009.state.gov/r/pa/prs/ps/2005/53490.htm.

5 Leon Sigal, "For North Korea, Verifying Requires Reconciling: The Lesson from A Troubled Past—Part I", 38 North, 14 December 2018, https://www.38north.org/2018/12/lsigal121418/; Leon Sigal, "For North Korea, Verifying Requires Reconciling: The Lesson from A Troubled Past—Part II", 38 North, 28 December 2018, https://www.38north.org/2018/12/lsigal122818/.

challenge is fundamentally different from the one that existed in 1992, as denuclearization would have to start from a point where one State possesses an active nuclear arsenal and a functioning nuclear complex.[6]

The Security Council repeatedly has called on the Democratic People's Republic of Korea to "abandon all nuclear weapons and existing nuclear programs in a complete, verifiable and irreversible manner." It has imposed a series of sanctions on its various activities.[7]

The most recent diplomatic initiative toward denuclearization was initiated in 2018. It involved a series of high-level meetings between the two States of the peninsula and a summit meeting in April 2018 in Panmunjom that resulted in a joint declaration in which both States "confirmed the common goal of realizing, through complete denuclearization, a nuclear-free Korean peninsula".[8] These contacts also resulted in a series of steps aimed at reducing the level of military tensions on the Korean peninsula. The Democratic People's Republic of Korea announced that it was unilaterally suspending nuclear and long-range ballistic missile tests and that it would shut down the Punggye-ri site where it conducted nuclear tests.

In a notable development, in June 2018, the United States and the Democratic People's Republic of Korea held their first summit in Singapore. In the joint statement issued, the Democratic People's Republic of Korea committed "to work toward complete denuclearization of the Korean Peninsula", reaffirming the earlier commitment made in Panmunjom, albeit in a rather non-specific way.[9] This meeting was followed by two other summits, in Hanoi in February 2019 and a brief meeting at the border in June 2019. In Hanoi, the two parties attempted to reach an agreement on specific steps toward denuclearization, but their understanding of these steps were too far apart. They did confirm in broad terms their commitment to continuing the discussion, although an attempt to launch a working-level dialogue has failed.

The current status of this engagement process is uncertain. In January 2020, the Democratic People's Republic of Korea announced that it was no longer "unilaterally bound" by its previous commitments, which apparently included the suspension of long-range ballistic missile and nuclear tests. The Democratic People's Republic of Korea announced later that it had "dropped the interest in dialogue" with the United States and that it will focus on building up a "more reliable force to cope with the long-term military threats" from the United States.[10] However, the Democratic People's Republic of Korea has not acted on its implied threat to resume nuclear and long-range missile tests and all parties appear to keep open the possibility of resuming dialogue.

6 South Africa eliminated its nuclear weapons before it joined the NPT and placed nuclear facilities under IAEA safeguards. Soviet nuclear weapons in Belarus, Kazakhstan, and Ukraine were not under operational control of the host States. All these weapons were subsequently transferred to the Russian Federation.
7 Security Council, resolution 2375, 11 September 2017, http://unscr.com/en/resolutions/2375.
8 "Panmunjom Declaration for Peace, Prosperity and Unification of the Korean Peninsula", Republic of Korea Ministry of Foreign Affairs, 27 April 2018, http://www.mofa.go.kr/eng/brd/m_5478/view.do?seq=319130.
9 "Joint Statement of President Donald J. Trump of the United States of America and Chairman Kim Jong Un of the Democratic People's Republic of Korea at the Singapore Summit", The White House, 12 June 2018, https://www.whitehouse.gov/briefings-statements/joint-statement-president-donald-j-trump-united-states-america-chairman-kim-jong-un-democratic-peoples-republic-korea-singapore-summit/.
10 "New Department Director General of DPRK Foreign Ministry for Negotiations with U.S. Issues Statement", *Uriminzokkiri*, 30 March 2020, http://www.uriminzokkiri.com/index.php?ptype=cfodoc&stype=0&lang=eng&mtype=view&no=27645; "Our Message to U.S. Is Clear: Ri Son Gwon, Minister of Foreign Affairs of DPRK", KCNA Watch, 12 June 2020, https://kcnawatch.org/newstream/1591940601-72980278/our-message-to-u-s-is-clear-ri-son-gwon-minister-of-foreign-affairs-of-dprk/.

THE CHALLENGE OF DENUCLEARIZATION

The difficulty of achieving tangible progress towards denuclearization testifies to the complexity of the technical and political issues involved. Indeed, the very concept of denuclearization remains contested. Security Council resolutions call for "complete, verifiable and irreversible" elimination of the nuclear weapons of the Democratic People's Republic of Korea, a position shared by most States that are engaged with the issue. The Democratic People's Republic of Korea, however, may have a different understanding of denuclearization and it has been suggested that its commitment to the process should not be understood as an offer to dismantle its nuclear weapon programme.[11] While this is probably correct today, the importance of the commitment to the process, if not to the end goal of that process, should not be underestimated. Political circumstances can change, sometimes quite dramatically and unexpectedly, in ways that might create space for progress toward denuclearizing the Korean Peninsula.

In theory, dismantlement of a nuclear programme is a relatively straightforward process that involves a number of well-defined steps. It would begin with a declaration of all nuclear facilities and materials, which would serve as a starting point of a programme to verify correctness and completeness of the declaration and to place the materials and facilities under safeguards.[12]

In practice, however, direct application of an approach that starts with a complete declaration presents a number of problems. Most important, it is difficult to expect that the Democratic People's Republic of Korea would be willing to disclose information about locations of its nuclear weapons or all of the facilities that are involved in weapon-related activities. The Democratic People's Republic of Korea's nuclear arsenal is probably the most valuable military asset that it possesses, so it will most certainly avoid taking any steps that would put it in danger.

Even if the Democratic People's Republic of Korea releases information about all its nuclear activities, verifying the correctness and completeness of that declaration would take considerable time. Given the difficult history of the efforts to curtail the Democratic People's Republic of Korea's nuclear programme, it is certain that others will suspect the Democratic People's Republic of Korea of concealing some of its facilities and weapons. This will present the State with the challenge of proving a negative. This challenge would be especially acute if the actual size of its nuclear programme is smaller than the existing intelligence estimates of concerned States assume. In this environment, verifying the absence of undeclared weapons, materials and facilities would, in effect, require unrestricted access to the entire territory of the Democratic People's Republic of Korea, which its leadership is unlikely to offer. The scale of its existing nuclear programme would also make it extremely difficult to reach a definitive conclusion about the absence of weapons and materials.[13]

11 Jeffrey Lewis, "Has Singapore Led to Real Gains on the North Korean Nuclear Question?", *Global Asia*, vol. 13, no. 4, 2018, https://www.globalasia.org/v13no4/cover/has-singapore-led-to-real-gains-on-the-north-korean-nuclear-question_jeffrey-lewis.

12 See, for example, David Albright, "Denuclearizing North Korea", Institute for Science and International Security, 14 May 2018, p. 5, https://isis-online.org/uploads/isis-reports/documents/Albright_North_Korea_slides_for_denuclearization_talk_may_14%2C_2018_final.pdf. The International Atomic Energy Agency has an established procedure that could be used to carry out all necessary verification activities: "Guidance for States Implementing Comprehensive Safeguards Agreements and Additional Protocols", IAEA, 2016, http://www-pub.iaea.org/MTCD/Publications/PDF/SVS-21_web.pdf.

13 The work of the United Nations Monitoring, Verification and Inspection Commission in Iraq in 1999–2003 suggests that such a verification programme can be carried out effectively in some circumstances. See, for example, Trevor Findlay, "Looking Back: The UN Monitoring, Verification and Inspection Commission", *Arms Control Today*, 2005, https://www.armscontrol.org/act/2005-09/looking-back-un-monitoring-verification-inspection-commission. Iraq, however, never produced weapon-usable fissile materials.

It is undoubtedly the case that identifying all nuclear activities will be an essential element of a "complete, verifiable, and irreversible dismantlement" of the Democratic People's Republic of Korea's nuclear programme. However, demanding a comprehensive declaration of all of the State's fissile materials and the immediate shutdown of all its nuclear facilities at the start of the process would be unrealistic and may even be counterproductive.[14]

An alternative approach would pursue the denuclearization programme as a series of steps that would open the Democratic People's Republic of Korea's nuclear programme gradually, by limiting certain activities and shutting down critical parts of the nuclear complex. This approach could also be designed in a way that allows parties to the process to gradually build trust, prove their commitment, and provide appropriate incentives, such as sanctions relief and gradual normalization of relations.[15]

One of the first and important steps in this sequence would be a suspension of known nuclear activities. This approach could accept a measure of interim uncertainty and focus on known production facilities. For example, there are strong reasons to believe that verified dismantlement of the Yongbyon nuclear complex would seriously constrain the Democratic People's Republic of Korea's nuclear programme as it would liquidate its only source of plutonium and tritium, which can be produced by the 5 MWe nuclear reactor, shown on figure 1. It would also substantially reduce its capacity to enrich uranium.[16] The verification programme could then be gradually expanded beyond Yongbyon.

Implementing this approach, however, will have to deal with uncertainty about the true scope of the nuclear programme. Questions about the possibility of continuing production at undeclared facilities will persist, undermining the political process. This is exactly what happened at several points in the past. The discovery of an undeclared uranium enrichment programme was a major factor in the unravelling of the 1994 Agreed Framework that verifiably suspended the production of plutonium. In 2008, the disagreement over the scope of verification undermined the attempt to reach an agreement within the framework of the Six-Party Talks. After the first summit between the United States and the Democratic People's Republic of Korea, US intelligence agencies reportedly assessed that the Democratic People's Republic of Korea was concealing parts of its programme and continuing production of fissile materials for nuclear weapons.[17] All this strongly suggests that any future arrangement will have to find a way to address the issue of undeclared production facilities and probably that of nuclear weapons as well.

14 Siegfried Hecker, "Why Insisting on a North Korean Nuclear Declaration Up Front Is a Big Mistake", 38 North, 28 November 2018, https://www.38north.org/2018/11/shecker112818/; "US Non-Proliferation Expert Proposes Roadmap with Reciprocal Benefits for NK-US Denuclearization Talks", *Hankyoreh*, 7 December 2018, http://english.hani.co.kr/arti/english_edition/e_northkorea/ 873515.html.

15 Siegfried S. Hecker, Robert L. Carlin, and Elliot A. Serbin, "A Technically-Informed Roadmap for North Korea's Denuclearization", Center for International Security and Cooperation, Stanford University, 28 May 2018, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/hecker_carlin-serbin_denuc_rlc.pdf; R. Scott Kemp, "North Korean Disarmament: Build Technology and Trust", *Nature*, 7 June 2018, https://doi.org/10.1038/d41586-018-05383-8; Alexander Glaser and Zia Mian, "Denuclearizing North Korea: A Verified, Phased Approach", *Science*, vol. 361, no. 6406, 7 September 2018, pp. 981–983, https://doi.org/10.1126/science.aau4817; Toby Dalton, Ariel (Eli) Levite, and George Perkovich, "Key Issues for U.S.–North Korea Negotiations", Carnegie Endowment for International Peace, 4 June 2018, https://carnegieendowment.org/2018/06/04/key-issues-for-u.s.-north-korea-negotiations-pub-76485; John Carlson, "Denuclearizing North Korea: The Case for a Pragmatic Approach to Nuclear Safeguards and Verification", Stimson Center, 2019, https://www.38north.org/reports/2019/01/jcarlson012419/.

16 Siegfried S. Hecker, Robert Carlin, and Elliot Serbin, "The More We Wait, The Worse It Will Get", 38 North, 4 September 2019, https://www.38north.org/2019/09/sheckerrcarlineserbin090419/; Gary Samore, "How Significant Is the Dismantlement of Yongbyon?", 38 North, 11 March 2019, https://www.38north.org/2019/03/gsamore031119/.

17 "North Korea Has Increased Nuclear Production at Secret Sites", *NBC News*, 30 June 2018, https://www.nbcnews.com/news/north-korea/north-korea-has-increased-nuclear-production-secret-sites-say-u-n887926.

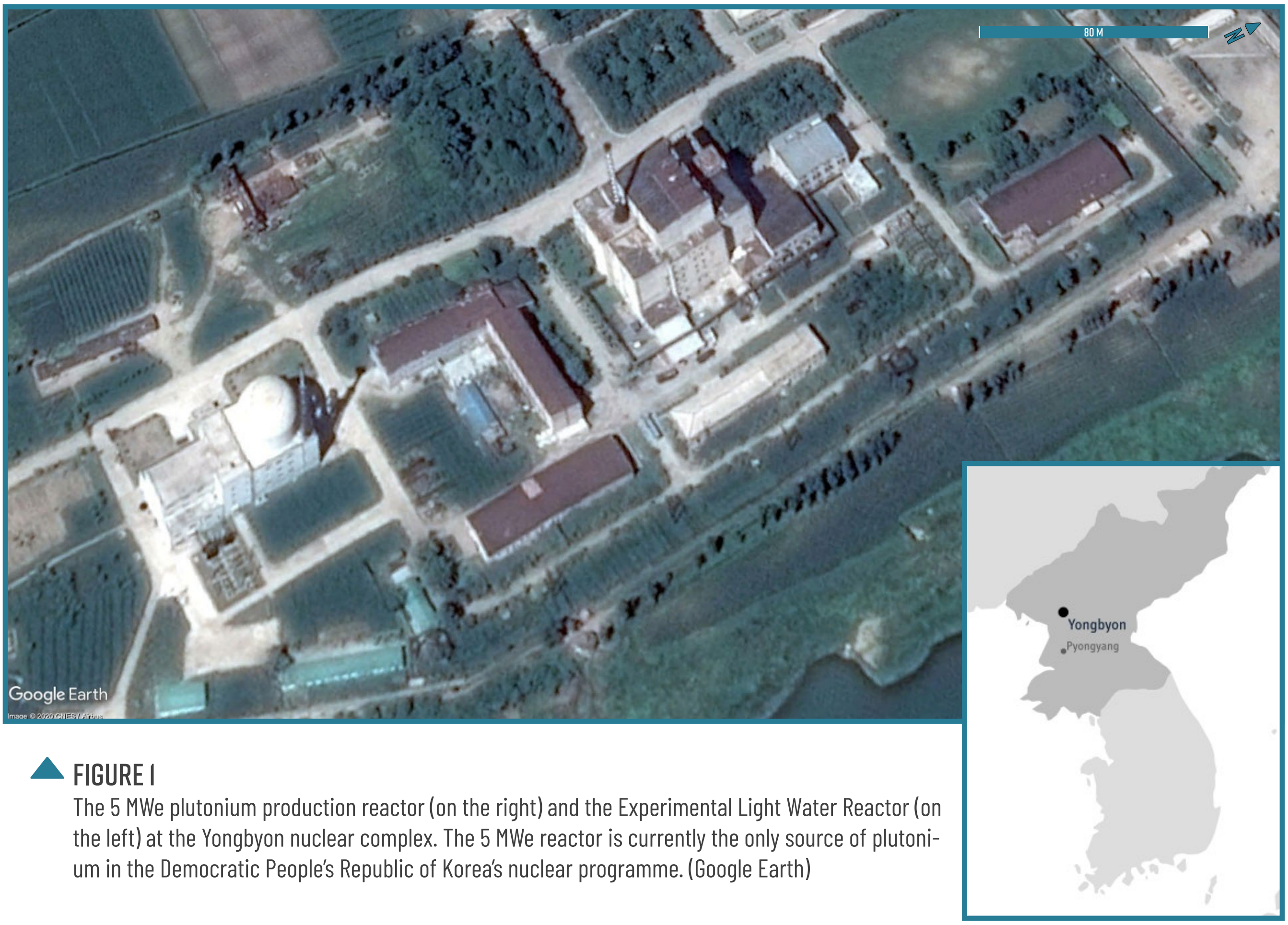

FIGURE 1

The 5 MWe plutonium production reactor (on the right) and the Experimental Light Water Reactor (on the left) at the Yongbyon nuclear complex. The 5 MWe reactor is currently the only source of plutonium in the Democratic People's Republic of Korea's nuclear programme. (Google Earth)

It also places a set of challenging and conflicting requirements on any future verification arrangements. A viable verification programme should be able to provide sufficient confidence in the absence of continuing production. At the same time it would have to operate in an environment in which inspectors may not have confidence in the completeness of the initial declaration and do not have access to important parts of the nuclear complex, such as weapons and weapon-related activities.

This report proposes an arrangement that could satisfy these conflicting requirements. It suggests a way to implement a process that would verifiably limit the Democratic People's Republic of Korea nuclear programme and launch a verification programme that would lead to its dismantlement or conversion to peaceful purposes.

A VERIFIABLE FREEZE OF FISSILE MATERIAL PRODUCTION: KEY ELEMENTS

The central obligation of the arrangement proposed here is a freeze on production of fissile materials. The benefits of such a freeze are widely acknowledged and understood. It would cap the Democratic People's Republic of Korea's nuclear arsenal and create conditions for a permanent end of production of weapon-usable fissile materials. The option of resuming some civilian activities in the future would most likely remain open, provided they are placed under appropriate safeguards.[18] At the first stage of the process, however, the obligation to end production should cover all nuclear cycle activities in order to facilitate verification.

One of the key features of the proposed arrangement is that verifying a freeze on fissile material production does not rely on a comprehensive list of all nuclear facilities. While production facilities would have to be declared, some parts of the nuclear complex (weapon-related facilities in particular) could be left out of the initial declaration. That declaration, however, would have to include information about the total amount of produced fissile materials. In combination with a properly structured verification programme, this information would enable a confirmation of compliance with the freeze on production.[19]

The commitment to freeze production of fissile materials would have to cover all nuclear cycle activities—reprocessing, enrichment, nuclear reactors, uranium conversion as well as uranium mining and milling. These facilities would have to be declared and placed under monitoring to verify their shutdown status. The initial declaration would be expected to include known production sites—the Yongbyon nuclear complex in particular. It would include facilities beyond Yongbyon as well, at least uranium mining and milling facilities and probably others. Confidence in the accuracy of that initial declaration is likely to be rather low, but it would provide a starting point for the verification process.

Nuclear materials at the production sites would have to be declared and properly secured to ensure their non-diversion and to facilitate the next step of the verification programme. It would involve an analysis of production and operating records of the facilities that are placed under monitoring and taking the inventory of nuclear materials located there. This would provide a consistency check that should be sufficiently accurate to detect signs of substantial undeclared past or present production activities. Taken together, the inventory of materials at the production sites, the examination of material flows and the information about the total amount of produced material should allow a degree of confidence to be established about the correctness and completeness of the information on materials and facilities provided in the initial declaration.

An important element of the proposed arrangement is the way it deals with materials in the military programme. As mentioned earlier, the initial declaration is only expected to include information about the fissile material production cycle. This means that facilities involved in weaponization activities would not be revealed, such as manufacturing of weapon components or

18 To the extent possible, the future activities would be consistent with the 1992 commitment not to possess enrichment or reprocessing facilities.

19 This approach is built on the concept of deferred verification that was developed in the context of the Fissile Material Cut-off Treaty; Pavel Podvig and Joseph Rodgers, *Deferred Verification: Verifiable Declarations of Fissile Material Stocks*, UNIDIR, 2017, https://unidir.org/files/publications/pdfs/deferred-verification-verifiable-declarations-of-fissile-material-stocks-en-694.pdf.

weapon assembly, or the handling of nuclear weapons. The verification programme, however, could operate and reach its goal without having access to any materials in military use or to the sites that handle them. To make this possible, the initial declaration should include information about the amount of material transferred to military activities. While this material would not be accessible, the removals will be visible to inspectors as they analyse the production history, so the military material would still be accurately accounted for. The actual verification of this part of the declaration would be deferred until such time as all nuclear weapons of the Democratic People's Republic of Korea are eliminated and the material they contained is presented for an inspection.[20]

This approach to handling military materials and nuclear weapons would mean that the Democratic People's Republic of Korea will be able to retain its nuclear arsenal for some period of time. That period, however, would not be indefinite. Importantly, the freeze would be a step forward from the current situation, in which the State not only keeps its weapons but continues to produce fissile materials to expand it. The approach to a freeze on fissile material production suggested here would provide a practical way to start a verification process that will account for all nuclear activities and materials and to create conditions for the elimination of nuclear weapons. The following section describes the arrangement in more detail.

20 Ibid.; a similar approach, a 'separation' of military materials, was also suggested in John Carlson, "Denuclearizing North Korea: The Case for a Pragmatic Approach to Nuclear Safeguards and Verification", Stimson Center, 2019, https://www.38north.org/reports/2019/01/jcarlson012419/.

DETAILS OF THE FREEZE ARRANGEMENT

VERIFICATION OBJECTIVES

For the freeze arrangement to work, it must include a verification mechanism that ensures the parties observe the terms of the agreement. In the past, verification was one of the most contentious issues between the Democratic People's Republic of Korea and its counterparts. It is therefore important to carefully define the scope and goals of verification activities and agree on the tools that can be used to achieve those goals. It will also be necessary to acknowledge practical limits on what verification can realistically accomplish. Some of these limits, such as access to certain sites, are political in nature and therefore can be negotiated. Others are more fundamental, such as the limit of accuracy that can be achieved in accounting for materials in the nuclear cycle.

A defining characteristic of verification that distinguishes it from other activities, such as monitoring or intelligence gathering, is that it is linked to an agreement and the obligations it contains. Verification has been defined as "a set of national and cooperative activities, tools, procedures, analytical processes, and fundamentally, judgments about what is happening with regard to specific activities defined in an agreement".[21] The verification system to accompany the freeze agreement would focus on its central obligation—the end of production of fissile materials.

This, in turn, means that the verification arrangements and verification goals in the freeze agreement would be different from those required to implement complete, verifiable and irreversible disarmament. The NPT obligations and safeguards can be considered as a baseline requirement for the latter. Table 1 compares the main verification-related features of the NPT and the 'freeze on production' arrangement. It should be emphasized that the goal of the freeze is not to replace the NPT obligations, but rather to begin transition to the Democratic People's Republic of Korea's eventual accession to the treaty.

The key difference between the two approaches in table 1 is that the central obligation assumed by the NPT non-nuclear-weapon State parties is not to acquire nuclear weapons. Verification of this obligation is achieved by placing all nuclear material in a State under safeguards to ensure that it remains in peaceful use. For a State with a comprehensive safeguards agreement in force, the IAEA can draw a conclusion of non-diversion of material placed under safeguards. If a State has an additional protocol in force, the IAEA can also reach a broader conclusion of the absence of undeclared nuclear material and activities.[22] IAEA safeguards focus on nuclear material, which is reflected in the first technical objective of comprehensive safeguards—the timely detection of diversion of significant quantities of nuclear materials.[23] The second technical objective—the detection of undeclared nuclear material and activities—sets an even stricter detection goal. In most cases gram quantities of nuclear material not reported to the IAEA would be considered undeclared.[24]

21 "Innovating Verification: New Tools & New Actors to Reduce Nuclear Risks. Overview", Nuclear Threat Initiative, 2014, p. 5, http://www.nti.org/media/pdfs/VPP_Overview_FINAL.pdf.

22 *IAEA Safeguards Glossary*, IAEA, 2002, para. 12.25, https://www.iaea.org/sites/default/files/iaea_safeguards_glossary.pdf.

23 *IAEA Safeguards Glossary*, para. 2.1.

24 A comprehensive safeguards agreement requires a State to establish a system of accounting for and control of nuclear material, which provides basis for the application of the safeguards. The IAEA uses grams as the unit of account for fissile materials, such as plutonium and HEU. *IAEA Safeguards Glossary*, IAEA, 2002, paras. 2.5, 3.3, 6.1, 6.8; "Guidance for States Implementing Comprehensive Safeguards Agreements and Additional Protocols", IAEA, May 2016, p. 21, http://www-pub.iaea.org/MTCD/Publications/PDF/SVS-21_web.pdf.

NON-NUCLEAR-WEAPON STATES IN NPT	A FREEZE ON PRODUCTION
Central obligation: All nuclear materials are in peaceful use	**Central obligation:** No production of fissile materials
Focus on materials: All materials (and facilities that handle them) are safeguarded to detect diversion	**Focus on production facilities:** All facilities that are capable of producing fissile materials are shut down
Production for peaceful uses is allowed and under safeguards	All production activities are suspended and subject to verification
All material is declared and placed under safe-guards	Military material is declared but not subject to verification
Technical objectives: Timely detection of diversion of one significant quantity of material Detection of undeclared nuclear material and activities	**Technical objectives:** Detection of undeclared operating production facilities Detection of undeclared nuclear material and production facilities

TABLE 1
Obligations and verification under the NPT for non-nuclear-weapon States and under a freeze on production

In contrast, in the freeze arrangement the verification goal would be to verify the absence of fissile material production. This means that the unit of detection is no longer a certain quantity of nuclear material diverted from declared activities. Instead, the technical objective of verification would be the detection of an operating production facility. While this might still be a challenging task, it is certainly easier than finding a small quantity of undeclared fissile material or detecting diversion from civilian activities.

Another important difference between these two verification arrangements is the suspension of all nuclear material production activities that would be part of the freeze (at least at its initial stages). Civilian nuclear activities that are allowed by the NPT create a backdrop that could complicate timely detection of diversion or undeclared activity. By suspending all production activities that involve nuclear materials, the freeze would create an environment in which undeclared production will be very difficult to conceal.

Finally, while the NPT demands that all nuclear material in a State be placed under safeguards, the freeze would allow the Democratic People's Republic of Korea to keep weapon-usable materials out of reach of the verification system—provided it declares the amount of material transferred to the weapons programme. (Details of this arrangement are described in a separate section below.) The fact that the Democratic People's Republic of Korea would be able to retain its nuclear weapons for some period of time has significant implications for the verification process as it directly affects the question of which technical objectives would make the verification effective.

A verification system can be considered effective if it can detect militarily significant violations in time to respond and deny a violator the benefits of the violation.[25] This is not the only way

25 See, for example, Amy F. Woolf, *Monitoring and Verification in Arms Control*, Congressional Research Service, 2011, p. 7, https://www.fas.org/sgp/crs/nuke/R41201.pdf.

to define verification effectiveness and indeed the IAEA safeguards adopt a somewhat different approach, in which the time for detecting diversion of material is determined by the time it takes to prepare that material for use in a nuclear explosive device.[26] The IAEA approach also relies on the concept of a militarily significant violation, even if implicitly. The technical objective of safeguards is to detect in a timely manner diversion of a significant quantity of nuclear material, defined as the approximate amount of material that would be required to build one nuclear weapon.[27]

The focus on one significant quantity is justified in the NPT context, where the acquisition of one nuclear weapon by a non-nuclear-weapon State could be considered a militarily significant violation. The calculus, however, would be quite different for a State that already possesses nuclear weapons. In such a case, a violation would be militarily significant if it could lead to a sizeable increase of the existing arsenal. In the context of a freeze on fissile material production the scale of the activity that the verification system would be required to detect would have to be rather large. In effect, the unit of detection would be not just an operational production facility, but a facility with a substantial capacity. Operations of this facility would be associated with a significant footprint that would be difficult to hide if all declared production activity is suspended.

It is impossible to define what would constitute a substantial production capacity in the context of the freeze as the answer to this question is a matter of judgement. It would also depend on the size of declared fissile material stocks. In any event, the freeze arrangement should not imply that operations of sufficiently small production facilities would be permitted or tolerated, let alone include a specific value for their size. The freeze should include an obligation to stop all production activities, no matter how small, and the verification programme should be built accordingly. The threshold for violating the freeze agreement would be substantial and therefore the probability of detecting the violation would be rather high.

VERIFICATION AT DECLARED SITES

Once the agreement to suspend production of fissile materials is concluded, its parties will identify the verifying organization that would be entrusted with carrying out the verification programme. The starting point of this programme will be a declaration of all production facilities. For the agreement to be effectively verifiable, the list of facilities would have to include all facilities of the nuclear cycle—nuclear reactors, reprocessing and enrichment plants, as well as uranium conversion facilities and uranium mining and milling operations. The key elements of the Democratic People's Republic of Korea's nuclear complex are shown in figure 1. A detailed description of main production facilities can be found in the appendix.

Most of what is known about the Democratic People's Republic of Korea's production complex today comes from the declarations that the Democratic People's Republic of Korea submitted in the past and from what it has revealed to international observers. In 1992, when the Democratic People's Republic of Korea joined the NPT and concluded a safeguards agreement with the IAEA, the Democratic People's Republic of Korea declared seven facilities that would be subject to safeguards, six of which were located in Yongbyon. All of these facilities were part of the plutonium production programme—chiefly the 5 Megawatt electric (MWe) reactor, the

26 *IAEA Safeguards Glossary*, para. 3.15.

27 The significant quantities are 8 kg for plutonium or uranium-233 and 25 kg of uranium-235 in highly enriched uranium (more than 20% of uranium-235). The significant quantity for natural uranium is 10 tonnes. *IAEA Safeguards Glossary*, para. 3.14.

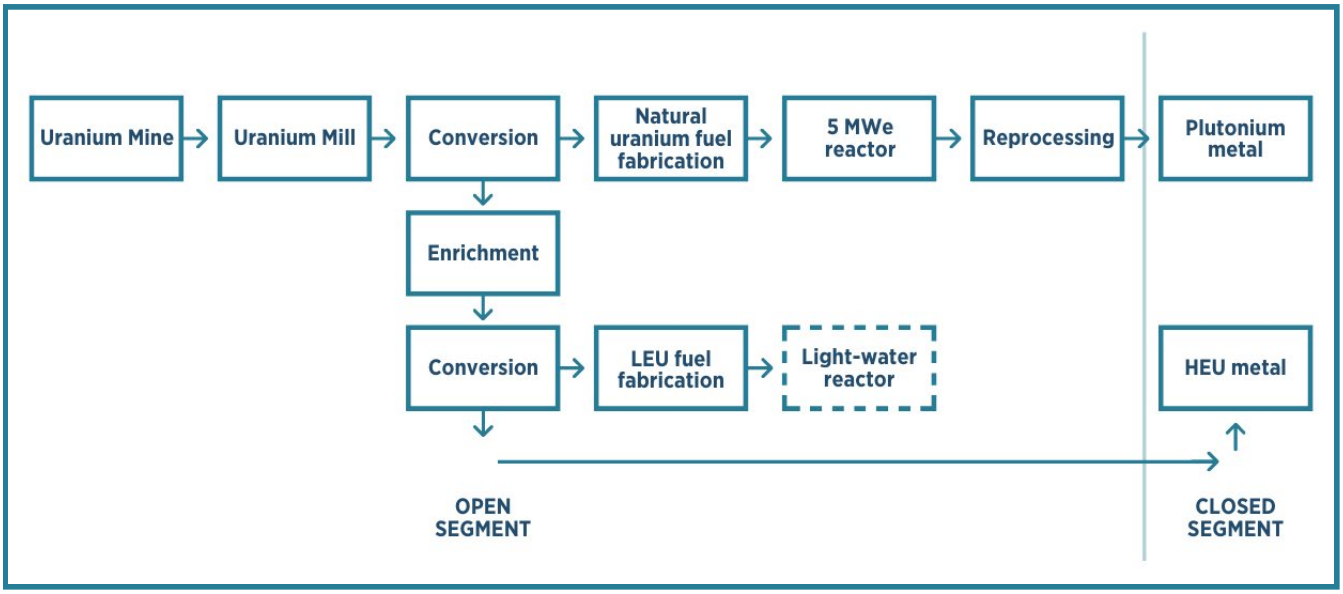

FIGURE 2

Key elements of the Democratic People's Republic of Korea's nuclear complex.

reprocessing plant, and the fuel fabrication and storage facilities.[28] The declaration also included two uranium mines and two milling facilities, located outside of Yongbyon.[29] In 2008, in the Six-Party Talks process, the Democratic People's Republic of Korea submitted a declaration that reportedly listed about fifteen nuclear facilities, at Yongbyon and at various universities.[30] That declaration apparently did not include information about the uranium enrichment programme or production facilities located outside of Yongbyon.

A declaration that would be submitted for the freeze on production agreement would include the Democratic People's Republic of Korea enrichment programme as well. Specifically, it would list the enrichment plant in Yongbyon as well as all other enrichment facilities. It would also include conversion facilities that produce uranium hexafluoride used in the enrichment process and convert enriched hexafluoride to other chemical forms suitable for other uses, such as uranium oxide for the Experimental Light Water Reactor or metal for use in weapons. It would also need to include information about uranium milling and mining.

Once the declaration is submitted, the verifying organization would start two linked but different processes—monitoring the shutdown of the declared facilities and verifying the completeness and correctness of the declaration of the total amount of produced material. For the latter process, the material at the declared production facilities would be placed under appropriate monitoring to prevent its diversion and facilitate the closing of the material balance.

All declared facilities would be shut down and placed under monitoring to ensure that they are not operating. In most cases this monitoring should not present any significant challenges. In-

28 Security Council, UN document S/1994/1310, 18 November 1994, http://digitallibrary.un.org/record/165777. It would be more accurate to refer to the 5 MWe reactor as a 20 MWt production reactor since electric power production was not its primary mission. The list also included two gas-cooled reactors that were under construction at the time and that were subsequently abandoned. The IRT research reactor in Yongbyon and critical and subcritical assemblies associate with it were already covered by item-specific safeguards. The seventh facility, outside of Yongbyon, appears to be "the radiochemical laboratory of the Institute of Radiochemistry (KDF)." Security Council, UN document S/1994/322, 22 March 1994, p. 7, http://digitallibrary.un.org/record/184928.

29 "Application of Safeguards in the Democratic People's Republic of Korea", IAEA document GOV/2011/53-GC(55)/24, 2 September 2011, para. 28, https://www.iaea.org/sites/default/files/gc/gc55-24_en.pdf.

30 Glen Kessler, "Far-Reaching U.S. Plan Impaired N. Korea Deal", *Washington Post*, 26 September 2008, http://www.washingtonpost.com/wp-dyn/content/article/2008/09/25/AR2008092504380.html.

deed, it has been suggested that the absence of activity at production sites could be monitored remotely by national technical means of participating States.[31] This approach might prove useful at the initial stages of implementation of the agreement, but in the end it would be important for the verifying organization to have access to the production facilities to apply seals or install monitoring equipment. The IAEA has a range of standard tools and procedures to monitor shutdowns that could be applied in this case. A facility could then be closed down, which is done by removing all nuclear material, or it could be decommissioned by removing essential equipment, or completely dismantled.[32] The term 'disablement' that is sometimes used in this context usually refers to decommissioning measures that can be reversed.

Monitored shutdown and disablement have been implemented in the Democratic People's Republic of Korea in the past, as part of the Agreed Framework in 1994–2002 and then in 2007–2009. This suggests that the application of similar measures for the purposes of the freeze agreement should not present significant challenges.

Reversibility of the shutdown measures would be subject to negotiation. In the past, the Democratic People's Republic of Korea was able to resume operations of almost all facilities that were placed under monitoring or disabled once the monitoring ended, which suggests that a truly irreversible shutdown is difficult to implement. The Democratic People's Republic of Korea has also expressed strong interest in maintaining a civilian nuclear programme and there are considerable benefits of keeping this option open as part of a cooperative threat reduction effort.[33] Therefore, the shutdown activity should anticipate that some facilities could resume operations as part of a peaceful nuclear programme once they are placed under appropriate safeguards. Some facilities, however, have little or no role in civilian applications, so it would be reasonable to negotiate their irreversible dismantlement. This, for example, would apply to the 5 MWe reactor and the reprocessing plant that were used to produce plutonium for the weapons programme.

CONFIRMING THE ABSENCE OF UNDECLARED FACILITIES

Verifying the completeness of the list of production facilities would be a significantly more challenging task. It should be expected that the confidence in any initial declaration submitted by the Democratic People's Republic of Korea would be low, especially if it does not include some facilities that the State is believed to operate outside of Yongbyon. The low level of confidence, however, should not prevent the verification organization from using that declaration as a starting point for the verification process.

The verification programme would rely primarily on an analysis of past production and material flows and material inventories at declared facilities. The material at the declared sites that would be placed under monitoring and be made available for verification would include materials in

31 See, for example, Alexander Glaser and Zia Mian, "Denuclearizing North Korea: A Verified, Phased Approach", Science, vol. 361, no. 6406, 7 September 2018, pp. 981–983, https://doi.org/10.1126/science.aau4817; Toby Dalton and George Perkovich, "Thinking the Other Unthinkable", Lawrence Livermore National Laboratory, 2020, p. 18, https://cgsr.llnl.gov/content/assets/docs/CGSR-LivermorePaper8.pdf.

32 See, for example, *IAEA Safeguards Glossary*, para. 5.29. For the IAEA, the life cycle of a facility ends at the decommissioning stage.

33 Siegfried S. Hecker, Robert L. Carlin, and Elliot A. Serbin, "A Technically-Informed Roadmap for North Korea's Denuclearization", Center for International Security and Cooperation, Stanford University, 28 May 2018, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/hecker_carlin-serbin_denuc_rlc.pdf; Lynn Rusten et al., "Building Security Through Cooperation. Report of the NTI Working Group on Cooperative Threat Reduction with North Korea", Nuclear Threat Initiative, 2019, https://media.nti.org/documents/NTI_DPRK2019_RPT_FNL.pdf.

a range of categories. It would be the materials tied up in the production process, such as uranium hexafluoride or irradiated reactor fuel, or the natural uranium-containing materials used for the fabrication of fuel for the 5 MWe reactor. Another category is civilian material, such as unirradiated fuel of the Experimental Light Water Reactor. Uranium concentrate at uranium mills and conversion plants would be included as well. The Democratic People's Republic of Korea might also declare materials located elsewhere to facilitate the closing of the material balance and confirm the accuracy of its material declaration. Material in military use would be declared separately, as described below.

The declaration of the total amount of produced fissile materials would then be used to ensure consistency of declarations and therefore the completeness of the list of facilities. It should be expected that the accurate reconstruction of production histories will be rather difficult as some records could be incomplete or missing. Accurate accounting for the material present at the production sites would also present a challenge. However, as discussed earlier, at this stage of the verification programme the unit of detection would be a production facility of a certain size, rather than a small amount of fissile material. With appropriate access to declared sites, a detailed analysis of material flows should be able to establish the presence or confirm the absence of major undeclared production facilities. The declaration of the total amount of produced material would be a necessary element of this process as it will provide a boundary condition for this analysis.

In the past, the Democratic People's Republic of Korea has provided information of the kind that would be required to implement the verified freeze arrangement. In 1992, it declared the amount of separated plutonium in its first submission to the IAEA.[34] In 2008, it declared that it possessed 37 kg of plutonium and turned over more than 18,000 pages of operating records from Yongbyon.[35] Thus, a data exchange of this kind is possible.

To be complete, the verification arrangements should also include a procedure for access to sites suspected of hosting an undeclared production facility. A provision of this kind would be important to have greater confidence in the absence of undeclared activities.[36] This was a highly contentious issue in the past, although the United States and the Democratic People's Republic of Korea made some progress towards a limited agreement in 2008.[37] The major point of disagreement that eventually made an agreement impossible was the issue of taking environmental samples at inspected sites.[38] Environmental sampling is a powerful tool and is a standard procedure for inspections that seek to determine the presence of nuclear material and activities. However, if the goal of an inspection is to certify the absence of ongoing production,

34 That declaration has been widely believed to be incomplete. However, the operational records shared by the Democratic People's Republic of Korea in 2008 appear to suggest that the declaration correctly reflected the amount of separated plutonium the State possessed at the time. See David Albright, "North Korean Plutonium and Weapon-Grade Uranium Inventories", Institute for Science and International Security, 7 October 2015, p. 5, http://www.isis-online.org/uploads/isis-reports/documents/North_Korean_Fissile_Material_Stocks_Jan_30_2015_revised_Oct_5_2015-Final.pdf.

35 "U.S.-North Korea Understandings on Verification", US Department of State, 11 October 2008, https://2001-2009.state.gov/r/pa/prs/ps/2008/oct/110924.htm.

36 It is important to note that this would only apply to the activity that would have to be declared—the production of fissile materials in this case. John Carlson, "IAEA Safeguards in North Korea", Stimson Center, 2020, p. 12, https://www.38north.org/wp-content/uploads/pdf/38-North-SR-2003-J-Carlson_IAEA-Safeguards-in-North-Korea.pdf.

37 Glen Kessler, "Far-Reaching U.S. Plan Impaired N. Korea Deal", *Washington Post*, 26 September 2008, http://www.washingtonpost.com/wp-dyn/content/article/2008/09/25/AR2008092504380.html; David Albright, "Denuclearizing North Korea", Institute for Science and International Security, 14 May 2018, https://isis-online.org/uploads/isis-reports/documents/Albright_North_Korea_slides_for_denuclearization_talk_may_14%2C_2018_final.pdf.

38 Glenn Kessler, "North Korea Doesn't Agree to Written Nuclear Agreement; Earlier Verbal Assurances Contradicted", *Washington Post*, 12 December 2008, http://www.washingtonpost.com/wp-dyn/content/article/2008/12/11/AR2008121103706.html; Leon Sigal, "For North Korea, Verifying Requires Reconciling: The Lesson from A Troubled Past—Part II", 38 North, 28 December 2018, https://www.38north.org/2018/12/lsigal122818/.

FIGURE 3
The facility known as Kangson has been identified as a possible location of a uranium enrichment plant. (Google Earth)

less intrusive tools might prove adequate.

A specific procedure would have to be facility-specific, but a number of solutions could be discussed. For example, it should be relatively straightforward to confirm the absence of centrifuges in a building suspected of containing an enrichment plant. One facility that may warrant such an inspection is the site known as Kangson (see figure 3). The possibility of an elaborate deception cannot be ruled out completely, but such a deception would be rather difficult to carry out if all fissile material production activities are stopped. If access to a facility is not possible, inspectors could verify the absence of non-nuclear signatures specific to the production process.[39] While detecting these signatures at long ranges is still technically difficult, sensors deployed in the vicinity of the facility could provide fairly high confidence in the absence of ongoing fissile material production. Remote monitoring could also play a role, for example in locating uranium mining and milling facilities.[40]

As is the case with other elements of the verification regime, on-site inspections at suspected production sites are not unprecedented. In 1999, the United States requested access to a site known as Kumchangri, where the Democratic People's Republic of Korea was suspected to be constructing a plutonium production complex. A visit to the site found no connection to the nuclear programme.[41]

39 R. Scott Kemp, "Environmental Detection of Clandestine Nuclear Weapon Programs", *Annual Review of Earth and Planetary Sciences*, vol. 44, no. 1, 2016, pp. 17–35, https://doi.org/10.1146/annurev-earth-060115-012526.
40 Melissa Hanham et al., "Monitoring Uranium Mining and Milling in China and North Korea through Remote Sensing Imagery", James Martin Center for Nonproliferation Studies, 2018, https://www.nonproliferation.org/wp-content/uploads/2018/10/op40-monitoring-uranium-mining-and-milling-in-china-and-north-korea-through-remote-sensing-imagery.pdf; Federico Derby and Sulgiye Park, "Mine Sweeping", *Jane's Intelligence Review*, October 2019, pp. 40–47.
41 James Risen, "Ferreting Out North Korea's Nuclear Secrets: U.S. Intelligence Experts at Odds", New York Times, 5 August 2000, https://www.nytimes.com/2000/08/05/world/ferreting-out-north-korea-s-nuclear-secrets-us-intelligence-experts-at-odds.html.

In the past, getting an agreement on verification was one of the most difficult parts of the negotiations with the Democratic People's Republic of Korea. The history of these negotiations, however, shows that with the right political incentives it should be possible to reach an agreement on key elements of the verification programme that would be required to implement a freeze on fissile material production. One important factor is that the structure of the freeze arrangement and its focus on relatively large facilities would allow the use of relatively non-intrusive tools and procedures that could still provide a high degree of confidence in the absence of continuing production.

MILITARY MATERIAL

Dealing with the military side of the Democratic People's Republic of Korea nuclear complex and the material that was used in the weapons programme is undoubtedly the most serious challenge for any future denuclearization effort. It is extremely unlikely that the Democratic People's Republic of Korea would be willing to disclose any information about its military activities, facilities, or weapons. In the standard approach to verification this presents an insurmountable problem as it makes accounting for nuclear material impossible. The United States has consistently sought full access to such information and political pressure to demand from the Democratic People's Republic of Korea "a full, complete and verifiable declaration of all its nuclear activities" will be part of any future talks.[42] This pressure will persist even though an analysis of technical complexities involved in verifying this declaration shows that this approach might not be productive.[43]

The arrangement described here would provide a way to address the issue of military materials as it requires the Democratic People's Republic of Korea to submit a declaration that would be verifiable but does not require an immediate disclosure of all locations and facilities. Verifying the declaration would be deferred until such time as the State's nuclear warheads are dismantled and eliminated.

This deferred verification approach would be an integral part of the freeze on production of fissile materials. In addition to the declaration of the total amount of produced material required by the freeze, the Democratic People's Republic of Korea would be required to declare the amount of fissile materials it transferred to its military programme.[44] The locations where these materials are handled and stored, whether as bulk material, weapon components, or weapons, would not have to be disclosed. These locations would constitute a 'closed segment' of the nu-

42 The demand for a full declaration was included in a letter sent to the US President by a group of Democratic senators. "Joint Letter to President Trump", 4 June 2018, https://www.foreign.senate.gov/imo/media/doc/06-04-18%20Menendez%20joint%20letter%20to%20Trump%20on%20NK%20Summit.pdf. One of the most detailed verification proposals that the United States discussed with the Democratic People's Republic of Korea also contained provisions for full access to all materials; "Verification Measures Discussion Paper", Washington Post, 2008, https://www.washingtonpost.com/wp-srv/politics/documents/kesslerdoc_092608.pdf.

43 Siegfried Hecker, "Why Insisting on a North Korean Nuclear Declaration Up Front Is a Big Mistake", 38 North, 28 November 2018, https://www.38north.org/2018/11/shecker112818/.

44 The remaining material, including that located at the declared production facilities, would be subject to inspections and appropriate safeguards. This material would include the fuel for the Experimental Light Water Reactor—natural and low-enriched uranium (whether in hexafluoride, oxide or metal). It might also include weapon-grade materials that had not been transferred to weapon-related activities.

clear complex excluded from verification access.[45] It should be emphasized that the declaration would not require disclosure of the number of weapons, the fraction of material that is actually used in active weapons, or any details of weapon design.

This does not mean that the material in military programmes will remain unaccounted for. Transfers of material to the closed segment will be visible in the records of the production complex that is open to inspections. These, for example, would include the records of outgoing shipments of plutonium or highly enriched uranium (HEU) metal produced by metallurgy facilities in Yongbyon. Since the amount of military material could be declared with relatively high accuracy, the fact that the destination of these shipments is not revealed and therefore the material cannot be accessed would not prevent inspectors from closing the material balance. Indeed, the process of closing the material balance itself would provide a first check of the accuracy of the military material declaration as it should be able to reveal any significant discrepancies between the declared amount of military material and the actual amount of material that has been removed from the open segment.

In the end, the declaration's correctness will be verified at the point in time when material is removed from the closed segment. Once the disarmament process reaches the point of eliminating nuclear weapons, the material that they contained would be presented to the verification body to confirm that the amount corresponds to that included in the initial declaration. This assumes that, by that time, the verification organization has confidence in the absence of undeclared fissile materials in the open segment. The removal of weapon material from the closed segment would liquidate that segment and extend the conclusion about the absence of undeclared material to the entire territory of the State.

The fact that some fissile materials have been used in nuclear tests could complicate the final closure of the closed segment since that material is difficult to accurately account for. However, when the verification process advances that far, it should be possible to determine the amount of material consumed in tests by combining documented accounts of the tests with drill-backs into the test tunnels.

The discussion of materials in military use should also mention tritium. Although not a fissile material, tritium is probably used in thermonuclear or boosted weapons in the Democratic People's Republic of Korea's arsenal.[46] Tritium is an isotope of hydrogen that is normally produced by irradiating lithium-6 targets in a nuclear reactor. Since the half-life of tritium is about twelve years, maintaining an active arsenal of weapons requires constant production of the isotope. Since the freeze on production arrangement would stop operations of nuclear reactors or allow restarting them only under safeguards, the production of tritium would be discontinued even if it would not be explicitly mentioned in the arrangement. While this has clear benefits for the denuclearization process, it might become an obstacle on the way to the agreement if the Democratic People's Republic of Korea wanted to preserve its tritium production capability. On the other hand, assuming that the Democratic People's Republic of Korea has several weapons in its current arsenal that use tritium, it would be able to keep half as many weapons in 12 years

45 Even though the closed segment would include a number of specific locations, such as weapon assembly facilities, these would not have to be declared at the outset. In general, the closed segment may not have a fixed physical boundary as, for example, a nuclear weapon would be considered to be in the closed segment regardless of its physical location. See detailed discussion in Pavel Podvig and Joseph Rodgers, *Deferred Verification: Verifiable Declarations of Fissile Material Stocks*, UNIDIR, 2017, https://unidir.org/files/publications/pdfs/deferred-verification-verifiable-declarations-of-fissile-material-stocks-en-694.pdf.

46 Siegfried S. Hecker, Chaim Braun, and Chris Lawrence, "North Korea's Stockpiles of Fissile Material", *Korea Observer*, vol. 47, no. 4, 2016, pp. 742–743.

and would probably still have some weapons of this type in 24 years. If denuclearization has a chance of succeeding, this would be the approximate timeframe for addressing the key issues. The uncertainty in the way tritium has been produced and used will help the Democratic People's Republic of Korea maintain the deterrence value of its weapons throughout this process even though its production would stop.

The downside of this approach to military materials is that the Democratic People's Republic of Korea would continue to possess an active nuclear arsenal. However, this arrangement would not legitimize the Democratic People's Republic of Korea as a nuclear-armed State since it explicitly includes a commitment to eliminate all nuclear weapons. The elimination process is an integral element of the verification arrangement, even though it is not implemented immediately.

Two additional considerations should be taken into account. The deferred dismantlement of nuclear weapons should be compared to the current situation, in which the Democratic People's Republic of Korea keeps its nuclear weapons and continues to produce weapon-usable fissile materials. The option to postpone the dismantlement would also give the Democratic People's Republic of Korea an assurance that it will maintain its leverage during the denuclearization process, which should make it easier to start this process and bring it to conclusion.

THE VERIFICATION ORGANIZATION

There are several possible approaches to identifying an organization to verify the freeze. There are significant advantages of entrusting this task to the IAEA, which has the necessary expertise and the organizational capacity to support complex verification missions. The statute of the Agency directly authorizes it "to apply safeguards, at the request of the parties, to any bilateral or multilateral arrangement".[47] Since the design of the described arrangement assumes that inspectors do not have access to material in the weapons complex, there would be no limits on participation of IAEA inspectors.[48]

The safeguards that would be applied as part of the freeze agreement would be different from the comprehensive safeguards that are administered as part of NPT obligations of non-nuclear weapon States or from item-specific safeguards applied to materials and facilities provided as technical assistance. The rights and obligations of all parties would be specified in a separate safeguards agreement that could be as broad or as narrow as the parties agree, provided they ensure the implementation of the freeze.[49]

The agreement should also envision the possibility of establishing safeguards in those cases when facilities are allowed to resume operations for peaceful purposes. These arrangements would probably have to be as strong as those included in an additional protocol as they would need to provide a strong guarantee of the absence of non-peaceful activity. This would also ensure gradual transition to applying the IAEA additional protocol standard to all activities in the Democratic People's Republic of Korea once all weapon-related activities are terminated.

Other approaches to verification are possible as well. For example, the process could be car-

47 Statute of the International Atomic Energy Agency, art. III.A.5, https://www.iaea.org/about/statute.
48 This is not necessarily a limiting factor as the IAEA has a procedure for selecting inspectors from nuclear weapon States to deal with proliferation-sensitive information.
49 For a detailed discussion of possible safeguards arrangements see John Carlson, "IAEA Safeguards in North Korea", Stimson Center, 2020, https://www.38north.org/wp-content/uploads/pdf/38-North-SR-2003-J-Carlson_IAEA-Safeguards-in-North-Korea.pdf.

ried out by a dedicated body created by the parties to the Six-Party Talks. Bilateral or regional arrangements have also been suggested as they could add value to the standard IAEA safeguards.[50] In any event, the participation of the IAEA, whether as the primary organization responsible for verification or as a consultative body, would be a valuable element of the process.

50 John Carlson, "Denuclearizing North Korea: The Case for a Pragmatic Approach to Nuclear Safeguards and Verification", Stimson Center, 2019, p. 13, https://www.38north.org/reports/2019/01/jcarlson012419/.

A PATH TO DENUCLEARIZATION

A verified freeze on fissile material production is not intended to be a goal in itself; it is rather a step that could open a path to denuclearization. Indeed, the structure of the verification provisions in this arrangement crucially depends on the commitment to end the production of fissile materials for non-peaceful purposes and to eliminate nuclear weapons.

Once the verification body confirms the suspension of all fissile material production activities and establishes the absence of undeclared production facilities, it would use the information about production histories and material flows to begin more accurate accounting for the material in the open segment of the nuclear complex.

By combining an increasingly detailed analysis of information about past production and material transfers with the physical inventory of the materials at the production sites, inspectors would start closing the material balance at various open sites. Eventually they would close the material balance in the open segment as a whole. If the declarations of the total amount of produced material and the amount of material removed to non-civilian uses were correct, the process of closing the material balance should confirm that. This would mean that it should be possible to certify the absence of undeclared material, both in the open segment and in the closed segment (that is, the part to which the inspectors would have no access).

One of the key advantages of this process is that, in addition to tracking down nuclear material and facilities, it provides a mechanism to continuously gauge the commitment to denuclearization and to build working relationships that are crucial for its success. In the end, these relationships and the record of cooperation would be as important for gaining confidence in the conclusions of the verification programme as well as the data it obtained.[51]

The goal of this process is to reach a level of confidence that would make it possible to move to the key element of the programme—elimination of nuclear weapons. Once that point is reached, the Democratic People's Republic of Korea would dismantle its nuclear weapons and submit the material they contained to the verification organization, which would provide the final check of the accuracy of the initial declaration.[52]

Getting to the point of dismantling nuclear weapons will take considerable time and effort. It will be impossible to reach unless a freeze on fissile material production and the subsequent dismantlement of the Democratic People's Republic of Korea military nuclear complex is part of a broader process that constrains other elements of the State's military complex, especially its ballistic missile programme.[53] This process will require a constant effort to sustain and expand the political dialogue and deal with inevitable setbacks. It will also require designing a set of incentives in the form of steps towards political normalization and graduated sanctions relief adjustable in response to specific measures implemented by the Democratic People's Republic of Korea. Most importantly, these efforts could be productive only if they lead to a significant change of the security environment in the region. Denuclearization may be a distant goal, but it is essential for peace and security on the Korean Peninsula.

51 R. Scott Kemp, "North Korean Disarmament: Build Technology and Trust", *Nature*, 7 June 2018, https://doi.org/10.1038/d41586-018-05383-8.

52 It is worth noting that the dismantlement process need not be monitored. Also, there would be no need for the Democratic People's Republic of Korea to disclose either the number of weapons it possessed or details of their design.

53 See, for example, Toby Dalton and George Perkovich, "Thinking the Other Unthinkable", Lawrence Livermore National Laboratory, 2020, https://cgsr.llnl.gov/content/assets/docs/CGSR-LivermorePaper8.pdf.

APPENDIX: NUCLEAR FACILITIES IN THE DEMOCRATIC PEOPLE'S REPUBLIC OF KOREA

The Democratic People's Republic of Korea began developing the capability to produce fissile materials in the 1980s with the construction of a nuclear reactor in Yongbyon. Since then it has deployed all components of a nuclear fuel cycle, from uranium mining to the production of plutonium and enriched uranium. The series of six nuclear tests, conducted in 2006–2017, demonstrated that the Democratic People's Republic of Korea has the capability to produce nuclear weapons. This appendix provides an overview of the key elements of the nuclear complex and outlines the extent of uncertainty about the scale of nuclear activities in the Democratic People's Republic of Korea.

PLUTONIUM PRODUCTION

The primary source of plutonium is the 5 Megawatt electric (MWe) gas-cooled graphite-moderated reactor at the Yongbyon nuclear center, which began operating in 1986.[54] The reactor uses natural uranium-based fuel clad in magnesium–aluminum alloy. The full load of the reactor core requires about 48 tonnes of natural uranium in 7,700 fuel rods.[55] In the normal operation regime, the fuel would stay in the core for about 3 years, after which it can be unloaded and moved to a cooling pond for subsequent reprocessing. In practice, the length of irradiation campaigns varied and so did the amount of plutonium that was separated from the irradiated fuel. It is estimated that the reactor can produce up to approximately 6 kg of plutonium per year.[56]

Reprocessing of irradiated fuel of the graphite reactor to separate plutonium is carried out at the Radiochemical Laboratory reprocessing facility in Yongbyon. The facility was designed to process about 100 tonnes of spent fuel a year, but it never operated at that capacity. Conversion of plutonium oxide into metal is carried out at the plutonium laboratory in Yongbyon. The metal is then shipped to a facility elsewhere for weaponization.[57]

Since details of the reactor operations are not publicly known, there is significant uncertainty in the estimate of the amount of plutonium it produced. There are several known irradiation and reprocessing campaigns, summarized in table 2. It appears that since the beginning of operation in 1986, there have been six full reloads of the reactor core, which would consume more than 300 tonnes of natural uranium.

54 Unless indicated otherwise, this section follows David Albright and Kevin O'Neill (eds.), *Solving the North Korean Nuclear Puzzle*, Institute for Science and International Security, 2000; Chaim Braun et al., "North Korean Nuclear Facilities After the Agreed Framework", Center for International Security and Cooperation, Stanford University, 27 May 2016, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/khucisacfinalreport_compressed.pdf; and Siegfried S. Hecker, Chaim Braun, and Chris Lawrence, "North Korea's Stockpiles of Fissile Material", Korea Observer, vol. 47, no. 4, 2016.

55 Robert Alvarez, "The North Korean Nuclear Program: Technical and Policy Issues", Johns Hopkins School of Advanced International Studies, 1 March 2018, p. 12.

56 Siegfried S. Hecker, Chaim Braun, and Chris Lawrence, "North Korea's Stockpiles of Fissile Material", *Korea Observer*, vol. 47, no. 4, 2016, p. 723.

57 Chaim Braun et al., "North Korean Nuclear Facilities After the Agreed Framework", Center for International Security and Cooperation, Stanford University, 27 May 2016, p. 36, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/khucisacfinalreport_compressed.pdf.

CAMPAIGN	UNLOADING	REPROCESSING	PLUTONIUM PRODUCTION	FUEL LOADED (METRIC TONNES OF URANIUM)
1986-1994	1989 (partial)	1990 (1989, 1991)	about 100 g	50–60
	1994	2003	20–30 kg	
2003–2005	2005	2005	10–14 kg	50
2005–2007	2007	2009	~8 kg	50
2013–2015	2015	2016	5.5–8 kg	50
2016–2018	2018	unknown		50
2018–	In reactor			50

TABLE 1
Summary of 5 MWe reactor operations and reprocessing campaigns[58]

The initial fuel load appears to have stayed in the reactor from 1986 to 1994, although a large number of failed fuel elements were removed from the core during that time.[59] In 1990, the Democratic People's Republic of Korea reprocessed some of the fuel elements removed from the reactor in what it declared to be the only reprocessing campaign before 1992.[60] The campaign appears to have produced a small amount of plutonium, probably less than 100 g.[61] An analysis of samples taken by the IAEA at the site in 1992 suggested that there were two additional reprocessing campaigns, in 1989 and 1991, raising suspicions that the State did not declare all plutonium separated before 1992. However, the reactor operating records turned over to the United States in 2008 apparently contained no evidence of additional plutonium production.[62]

58 Adapted from Siegfried S. Hecker, Chaim Braun, and Chris Lawrence, "North Korea's Stockpiles of Fissile Material", *Korea Observer*, vol. 47, no. 4, 2016, p. 731. Additional information from David Albright and Paul Brannan, "The North Korean Plutonium Stock, February 2007", Institute for Science and International Security, 20 February 2007, https://isis-online.org/uploads/isis-reports/documents/DPRKplutoniumFEB.pdf; David Albright, "North Korean Plutonium and Weapon-Grade Uranium Inventories", Institute for Science and International Security, 7 October 2015, p. 5, http://www.isis-online.org/uploads/isis-reports/documents/North_Korean_Fissile_Material_Stocks_Jan_30_2015_revised_Oct_5_2015-Final.pdf; "Application of Safeguards in the Democratic People's Republic of Korea", IAEA document GOV/2018/34-GC(62)/12, 20 August 2018, paras. 15, https://isis-online.org/uploads/iaea-reports/documents/DPRK_safeguards_report_IAEA_20Aug2018.pdf; "Application of Safeguards in the Democratic People's Republic of Korea", IAEA document GOV/2019/33-GC(63)/20, 19 August 2019, para. 12, https://www.iaea.org/sites/default/files/gc/gc63-20.pdf.

59 As of 1994, about 700 damaged fuel rods removed from the reactor were placed in a dry storage facility; Robert Alvarez, "The North Korean Nuclear Program: Technical and Policy Issues", Johns Hopkins School of Advanced International Studies, 1 March 2018, pp. 12, 14.

60 "Report by the Director General of the International Atomic Energy Agency on Behalf of the Board of Governors to All Members of the Agency on the Non-Compliance of the Democratic People's Republic of Korea", IAEA document INFCIRC/419, 8 April 1993, para. 6, https://www.iaea.org/sites/default/files/publications/documents/infcircs/1993/infcirc419.pdf.

61 Chaim Braun et al., "North Korean Nuclear Facilities After the Agreed Framework", Center for International Security and Cooperation, Stanford University, 27 May 2016, p. 42, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/khucisacfinalreport_compressed.pdf.

62 David Albright, "North Korean Plutonium and Weapon-Grade Uranium Inventories", Institute for Science and International Security, 7 October 2015, p. 5, http://www.isis-online.org/uploads/isis-reports/documents/North_Korean_Fissile_Material_Stocks_Jan_30_2015_revised_Oct_5_2015-Final.pdf.

The last time the reactor stopped operation for a sufficient length of time for refueling was in December 2018.[63] It is not clear if the irradiated fuel has been removed from the reactor. In any event, in its most recent assessment the IAEA concluded that "it is almost certain" that this fuel has not been reprocessed.[64]

Assuming that the fuel removed from the 5 MWe reactor in 2018 has not been reprocessed, the amount of separated plutonium in the Democratic People's Republic of Korea inventory is estimated to be between about 20 and 40 kg.[65]

In 2010, construction began on a different kind of reactor in Yongbyon, the Experimental Light-Water Reactor (ELWR).[66] Although reactors of this type are not well suited to producing weapon-grade plutonium, they could be adapted for this purpose. As of the end of 2019 the reactor did not appear to be operational, even though its external structure was completed in 2013.[67] It is almost certain that enough fuel has been produced for the initial reactor core load. The ELWR—a 100 Megawatt thermal (MWt) reactor—uses uranium oxide fuel enriched to 3.5% uranium-235. One core requires 4 tonnes of UO_2.[68] This means that the fuel load for the initial core required about 25 tonnes of natural uranium and 16,000 kg SWU of separative work to produce.[69] Once the reactor starts, its sustained operation would consume about 6.5 tonnes of natural uranium and about 4,000 kg SWU annually.

The Soviet-supplied research reactor at the Yongbyon Nuclear Center, known as IRT-DPRK or IRT-2000, is another potential source of plutonium. The reactor reached criticality in 1965, initially with uranium enriched to 10% uranium-235. Around 1974, the reactor was converted to HEU fuel with 80% uranium-235. After 1986, the reactor used fuel with uranium enriched to 36%. All fuel for the reactor and the associated critical assembly was provided by the Soviet Union, which supplied the last batch of fuel in 1991.[70] While the reactor could theoretically produce kilogram quantities of plutonium, it is not believed to be a significant source of the material.[71] It should also be noted that the reactor, as well as the critical and subcritical assemblies associated with it, were under IAEA monitoring until December 2002.[72]

63 "Application of Safeguards in the Democratic People's Republic of Korea", IAEA document GOV/2019/33-GC(63)/20. 19 August 2019, para. 12, https://www.iaea.org/sites/default/files/gc/gc63-20.pdf.
64 "Application of Safeguards in the Democratic People's Republic of Korea", IAEA document GOV2020/42-GC(64)/18. 1 September 2020, para. 12, https://www.iaea.org/sites/default/files/gc/gc64-18.pdf.
65 Siegfried S. Hecker, Chaim Braun, and Chris Lawrence, "North Korea's Stockpiles of Fissile Material", *Korea Observer*, vol. 47, no. 4, 2016, p. 731.
66 Chaim Braun et al., "North Korean Nuclear Facilities After the Agreed Framework", Center for International Security and Cooperation, Stanford University, 27 May 2016, pp. 17–21, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/khucisacfinalreport_compressed.pdf.
67 Elliot Serbin and Allison Puccioni, "North Korea's Experimental Light Water Reactor: Possible Testing of Cooling System", 38 North, 6 December 2019, https://www.38north.org/2019/12/yongbyon120519/.
68 Chaim Braun et al., "North Korean Nuclear Facilities After the Agreed Framework", Center for International Security and Cooperation, Stanford University, 27 May 2016, pp. 19–20, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/khucisacfinalreport_compressed.pdf.
69 1 kg SWU is a separative work unit, which is a standard measure of the effort required to separate a mass of feed into enriched product and waste.
70 Pavel Podvig (ed.), *The Use of Highly-Enriched Uranium as Fuel in Russia,* International Panel on Fissile Materials, 2017, p. 130, http://fissilematerials.org/library/rr16.pdf.
71 Siegfried S. Hecker, Chaim Braun, and Chris Lawrence, "North Korea's Stockpiles of Fissile Material", *Korea Observer*, vol. 47, no. 4, 2016, p. 729.
72 "Application of Safeguards in the Democratic People's Republic of Korea", IAEA document GOV/2011/53-GC(55)/24, 2 September 2011, para. 17, https://www.iaea.org/sites/default/files/gc/gc55-24_en.pdf.

URANIUM ENRICHMENT

The full scale of the uranium enrichment programme of the Democratic People's Republic of Korea is not known. The existence of the programme was publicly revealed in 2002, when the United States accused the State of building the capability to enrich uranium to circumvent the restrictions on plutonium production imposed by the Agreed Framework, which was in force at that time.[73] It does not appear, however, that the programme produced enriched uranium until a much later date—in 2007, the US intelligence community had only medium confidence that the programme was active.[74] In November 2010, an apparently operational Uranium Enrichment Workshop was demonstrated in Yongbyon to a group of US visitors. According to the accounts of that visit, the hosts disclosed that the facility contained 2,000 centrifuges with a total separative capacity of 8,000 kg SWU per year.[75] An expansion of the facility undertaken in 2013 doubled the facility footprint—and probably its capacity as well, to 16,000 kg SWU per year.[76]

There are strong reasons to believe that the centrifuge facility in Yongbyon is not the first or the only uranium enrichment plant in the Democratic People's Republic of Korea. The building that houses centrifuges was previously part of the Fuel Fabrication Facility, which was under IAEA monitoring until April 2009. At that time, there were no indications of new construction at the site. Given that the new facility was brought into operation in less than 20 months, it is certain that the Democratic People's Republic of Korea had extensive experience with operating centrifuges before the Uranium Enrichment Workshop was built, probably at one or more other facilities.[77] The number and locations of those facilities, however, are unknown.

By all indications, the Democratic People's Republic of Korea has operated at least a small-scale pilot enrichment facility that may be located outside of Yongbyon. One estimate suggested that in order to study operations of enrichment cascades, such a plant would have to include at least 660 centrifuges.[78] This would correspond to a total capacity of about 2,600 kg SWU per year. However, given the experimental nature of such a facility, the actual capacity might be somewhat smaller. This facility is believed to have been in operation since 2003.[79] The current status of the pilot facility is not known and it is possible that it was shut down and its centrifuges were transferred to the Uranium Enrichment Workshop in Yongbyon.[80]

It is also possible that in addition to the pilot plant there is a larger enrichment facility outside

73 See, for example, "Fact Sheet on DPRK Nuclear Safeguards", International Atomic Energy Agency, 25 July 2014, https://www.iaea.org/newscenter/focus/dprk/fact-sheet-on-dprk-nuclear-safeguards.
74 Glenn Kessler, "New Doubts on Nuclear Efforts by North Korea", *Washington Post*, 1 March 2007, http://www.washingtonpost.com/wp-dyn/content/article/2007/02/28/AR2007022801977.html.
75 Siegfried S. Hecker, "Return Trip to North Korea", Korea Economic Institute, 23 November 2010; Siegfried S. Hecker, "A Return Trip to North Korea's Yongbyon Nuclear Complex", Center for International Security and Cooperation, Stanford University, 20 November 2010, https://graphics8.nytimes.com/packages/pdf/world/2010/North_Korea_Report.pdf. It was subsequently confirmed that "each cascade held 344 centrifuges, for a total of 2,064 centrifuges". David Albright, "North Korean Plutonium and Weapon-Grade Uranium Inventories", Institute for Science and International Security, 7 October 2015, p. 15, http://www.isis-online.org/uploads/isis-reports/documents/North_Korean_Fissile_Material_Stocks_Jan_30_2015_revised_Oct_5_2015-Final.pdf.
76 David Albright and Robert Avagyan, "Recent Doubling of Floor Space at North Korean Gas Centrifuge Plant", Institute for Science and International Security, 7 August 2013, http://isis-online.org/uploads/isis-reports/documents/Yongbyon_fuel_facility_7Aug2013.pdf.
77 Chaim Braun et al., "North Korean Nuclear Facilities After the Agreed Framework", Center for International Security and Cooperation, Stanford University, 27 May 2016, p. 29, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/khucisacfinalreport_compressed.pdf.
78 Siegfried S. Hecker, Chaim Braun, and Chris Lawrence, "North Korea's Stockpiles of Fissile Material", *Korea Observer*, vol. 47, no. 4, 2016, p. 736.
79 Ankit Panda, *Kim Jong Un and the Bomb: Survival and Deterrence in North Korea*, 2020, p. 333.
80 Chaim Braun et al., "North Korean Nuclear Facilities After the Agreed Framework", Center for International Security and Cooperation, Stanford University, 27 May 2016, p. 29, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/khucisacfinalreport_compressed.pdf.

of Yongbyon. Indeed, the US intelligence community reportedly identified a large-scale enrichment plant, referred to as Kangson.[81] According to an intelligence assessment, as of 2018 the Kangson plant is capable of producing twice as much HEU as the facility in Yongbyon.[82] This would suggest that the plant's capacity could be as high as 32,000 kg SWU per year.[83]

One candidate for the Kangson facility, located in the Chollima district near Pyongyang, was identified by Jeffrey Lewis and his colleagues in 2018.[84] This identification, however, has been disputed. Without access to the site it is not possible to say with certainty that that facility is indeed an enrichment plant.[85]

Because of the uncertainties surrounding the enrichment programme of the Democratic People's Republic of Korea, the range of estimates of available capacity is rather large. On the low end, the Uranium Enrichment Workshop in Yongbyon with a capacity of 16,000 kg SWU per year is the only operational facility. On the high end of the estimates, the combined capacity of the pilot plant and the plants in Yongbyon and Kangson could be as high as 50,000 kg SWU per year.

While there is no direct evidence that the Democratic People's Republic of Korea uses its enrichment capacity to produce weapon-grade HEU, it is reasonable to assume that this is the case. It is also likely that some of the enrichment capacity was used to produce low enriched uranium to fuel the ELWR. The facility in Yongbyon probably produced enough material for one and a half cores of the ELWR. This corresponds to about 5.5 tonnes of uranium with an enrichment of 3.5%, which would require 40 tonnes of natural uranium in the feed and 25,000 kg SWU of separative work.

In the scenario that assumes that Yongbyon is the only enrichment facility, this would still leave about 85,000 kg SWU of separative work capacity to produce HEU through the end of 2019. This suggests that the Yongbyon plant alone could have produced as much as 400 kg of 90% HEU by the end of 2019. This process would have required about 85 tonnes of natural uranium.[86] The production capacity would be about 80 kg of 90% HEU a year from a feed containing about 16 tonnes of natural uranium.

It is clear that the addition of a second large enrichment facility would substantially increase the

81 David Albright, "On the Question of Another North Korean Centrifuge Plant and the Suspect Kangsong Plant", Institute for Science and International Security, 25 May 2018, https://isis-online.org/isis-reports/detail/on-the-question-of-another-north-korean-centrifuge-plant-and-the-suspect-ka/10; David Albright and Sarah Burkhard, "Revisiting Kangsong: A Suspect Uranium Enrichment Plant", Institute for Science and International Security, 2 October 2018, http://isis-online.org/uploads/isis-reports/documents/Kangsong_Update_2Oct2018_Final.pdf.

82 Ankit Panda, *Kim Jong Un and the Bomb: Survival and Deterrence in North Korea*, 2020, p. 112.

83 This would be consistent with the reported US estimate of 6,000–12,000 centrifuges installed at the Kangson plant; David Albright, "On the Question of Another North Korean Centrifuge Plant and the Suspect Kangsong Plant", Institute for Science and International Security, 25 May 2018, p. 2, https://isis-online.org/uploads/isis-reports/documents/Kangsong_25May2018_final.pdf.

84 Ankit Panda, "Revealing Kangson, North Korea's First Covert Uranium Enrichment Site", *The Diplomat*, 13 July 2018, https://thediplomat.com/2018/07/exclusive-revealing-kangson-north-koreas-first-covert-uranium-enrichment-site/.

85 Michael Madden, "Much Ado About Kangson", 38 North, 3 August 2018, https://www.38north.org/2018/08/mmadden080318/; David Albright and Sarah Burkhard, "Revisiting Kangsong: A Suspect Uranium Enrichment Plant", Institute for Science and International Security, 2 October 2018, http://isis-online.org/uploads/isis-reports/documents/Kangsong_Update_2Oct2018_Final.pdf.

86 There are a number of ways to optimize operations of a centrifuge facility to maximize HEU production and minimize the natural uranium requirements. This estimate does not take into account any special optimization measures. It assumes that the facility operated at the capacity of 8,000 kg SWU/year in 2011–2014 and 16,000 kg SWU/year after that. For a detailed treatment, see Chaim Braun et al., "North Korean Nuclear Facilities After the Agreed Framework", Center for International Security and Cooperation, Stanford University, 27 May 2016, p. 49–55, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/khucisacfinalreport_compressed.pdf; David Albright, "North Korean Plutonium and Weapon-Grade Uranium Inventories", Institute for Science and International Security, 7 October 2015, p. 15, http://www.isis-online.org/uploads/isis-reports/documents/North_Korean_Fissile_Material_Stocks_Jan_30_2015_revised_Oct_5_2015-Final.pdf.

	YONGBYON-ONLY	YONGBYON PLUS AN ADDITIONAL FACILITY
HEU inventory, end of 2019	400 kg	1,000 kg
Natural uranium consumed by the enrichment programme as of end 2019	125 tonnes	255 tonnes
HEU production capacity	80 kg/year	240 kg/year
Natural uranium required by the enrichment programme	16 tonnes/year	48 tonnes/year

TABLE 3
Estimated weapon-grade HEU inventory and natural uranium requirements of the enrichment programme

amount of HEU that the Democratic People's Republic of Korea could have produced. Assuming that the capacity of such a facility was increased gradually starting in 2010, it would have added about 128,000 kg SWU of cumulative capacity to the enrichment complex.[87] This would translate into additional 600 kg of 90% HEU produced by the end of 2019 and about 160 kg of 90% HEU per year production capacity after that. The corresponding natural uranium requirements would be 130 tonnes and 32 tonnes per year, respectively.

The results of this estimate are presented in table 3. The numbers are on the higher end of more detailed estimates, but not inconsistent with them, given the uncertainties surrounding the enrichment programme.[88] As discussed earlier, the available evidence strongly suggests the presence of a second enrichment facility. At the same time, there is a plausible, even if unlikely, scenario in which all current enrichment activities are concentrated in Yongbyon.

URANIUM CONVERSION

The term 'conversion' is usually used to refer to the chemical processes that convert uranium from one chemical form to another to prepare it for further use. Conversion is an important part of any fuel cycle as all uranium undergoes treatment at some point. In the fuel cycle of the 5 MWe reactor, conversion includes several steps that produce uranium metal from uranium oxide (U_3O_8, or 'yellowcake') received from a uranium milling plant. In the uranium enrichment cycle, the yellowcake has to be converted to uranium hexafluoride (UF_6), which is then fed into centrifuge cascades. Once the uranium is enriched to the required level it is converted either into uranium oxide (UO_2) for use in light-water reactor fuel or into metal.

The conversion facilities associated with the production of fuel for the 5 MWe reactor were located at the Fuel Fabrication Plant in Yongbyon.[89] The process involved reduction of yellowcake

87 This takes into account the US assessment of the Kangson plant being the first major enrichment facility as reported by Panda and follows the assumptions made by Braun et al. regarding the centrifuge manufacturing schedule. Ankit Panda, *Kim Jong Un and the Bomb: Survival and Deterrence in North Korea*, 2020, p. 333; Chaim Braun et al., "North Korean Nuclear Facilities After the Agreed Framework", Center for International Security and Cooperation, Stanford University, 27 May 2016, p. 52, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/khucisacfinalreport_compressed.pdf.

88 Siegfried S. Hecker, Robert L. Carlin, and Elliot A. Serbin, "A Comprehensive History of North Korea's Nuclear Program: 2018 Update", Center for International Security and Cooperation, Stanford University, 11 February 2019, p. 4, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/2018colorchartnarrative_2.11.19_fin.pdf.

89 Fuel for the first load of the reactor was produced at a pilot fuel fabrication plant that was in operation in 1983–1986. The facility was decommissioned before 1991. "Application of Safeguards in the Democratic People's Republic of Korea", IAEA document GOV/2011/53-GC(55)/24, 2 September 2011, para. 29, https://www.iaea.org/sites/default/files/gc/gc55-24_en.pdf.

to UO_2 and its subsequent treatment with hydrofluoric acid to produce uranium tetrafluoride (UF_4), which was then converted to metal.[90] During the Agreed Framework period (1994–2002) these facilities significantly deteriorated, but some of them were later reconstituted. In 2007, as part of disablement measures, the IAEA took an inventory of the equipment and material in the building.[91] The Agency also observed experimental equipment used to study the dry fluorination process.[92]

After the Democratic People's Republic of Korea terminated the disablement activities in 2009, the conversion line was reconstituted, although some processes were moved to different buildings. One of the Fuel Fabrication Plant buildings was refitted to host a uranium enrichment facility. The upgrade also must have added a UF_6 production line as well as a line of reconversion of UF_6 into UO_2 for use in fuel for the ELWR. As a result of this transformation, the Fuel Fabrication Plant in Yongbyon has been significantly expanded. By all indications, it can now produce uranium metal fuel for the 5 MWe reactor, uranium oxide fuel for the ELWR and uranium hexafluoride.[93]

While the Yongbyon Fuel Fabrication Plant appears to be the primary source of UF_6 for the enrichment programme, it is possible that there is another conversion facility. Since the Democratic People's Republic of Korea apparently operated some centrifuge facilities before 2009, it must have had a source of UF_6 to support such operations. Some evidence suggests that the State may have had access to UF_6 as early as 2001.[94] It is not clear, however, if that evidence is conclusive as the existence of a facility that could produce hexafluoride was not fully supported by US estimates at the time.[95]

It is possible that the Democratic People's Republic of Korea had some small-scale conversion facility outside of Yongbyon or, indeed, in one of the other buildings at the Yongbyon site. While IAEA inspectors were present at the site in 2007–2009, they did not have access to all of its buildings and detection of UF_6 production was not part of their mission. It is entirely possible that the State was able to produce substantial amounts of UF_6 in Yongbyon in the 2007–2009 period and had some limited-scale production before that.

URANIUM MINING AND MILLING

In its initial declaration to the IAEA in 1992, the Democratic People's Republic of Korea identified two uranium mines—Wolbisan Uranium Mine and Pyongsan Uranium Mine. It also listed two uranium concentrate plants—Pakchon Uranium Concentrate Pilot Plant and Pyongsan Uranium

90 Chaim Braun et al., "North Korean Nuclear Facilities After the Agreed Framework", Center for International Security and Cooperation, Stanford University, 27 May 2016, p. 31, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/khucisacfinalreport_compressed.pdf.

91 "Application of Safeguards in the Democratic People's Republic of Korea", IAEA document GOV/2007/45-GC(51)/19, 17 August 2007, para. 9(i), https://www.iaea.org/sites/default/files/gc/gc51-19_en.pdf.

92 "Application of Safeguards in the Democratic People's Republic of Korea", IAEA document GOV/2011/53-GC(55)/24, 2 September 2011, para. 29, https://www.iaea.org/sites/default/files/gc/gc55-24_en.pdf.

93 Chaim Braun et al., "North Korean Nuclear Facilities After the Agreed Framework", Center for International Security and Cooperation, Stanford University, 27 May 2016, p. 33–34, https://fsi-live.s3.us-west-1.amazonaws.com/s3fs-public/khucisacfinalreport_compressed.pdf.

94 The IAEA conducted an analysis of three transport cylinders containing UF_6 that were supplied to Libya in 2000 and 2001. The content of one of the cylinders was linked to the Democratic People's Republic of Korea. "Application of Safeguards in the Democratic People's Republic of Korea", IAEA document GOV/2011/53-GC(55)/24, 2 September 2011, para. 50, https://www.iaea.org/sites/default/files/gc/gc55-24_en.pdf.

95 Jeffrey Lewis, "Can North Korea Produce UF6?", ArmsControlWonk.com, 5 October 2005, https://www.armscontrolwonk.com/archive/200813/north-koreas-uf6-capability/; Paul Kerr, "News Analysis: Examining North Korea's Nuclear Claims", *Arms Control Today*, March 2005, https://web.archive.org/web/20110709205854/https://www.armscontrol.org/act/2005_03/NA_NorthKorea.

Concentrate Plant.[96] There is, however, significant uncertainty about the full extent of the uranium mining complex as well as the current status of its facilities. The lack of access also makes it difficult to estimate uranium content in the mined ore. These factors combined create significant uncertainty in the estimates of the amount of natural uranium produced and the amount of uranium ore that would be required to support the nuclear programme.[97] A geological analysis suggests that the Democratic People's Republic of Korea does not have an abundance of high-grade uranium ore on its territory, so it is likely that the mining activity is concentrated in the few places where uranium content in the ore is relatively high.[98]

It appears that the Pyongsan Uranium Mine and the Pyongsan Uranium Concentrate Plant located nearby is the primary uranium extraction complex. The milling facility has been expanded in recent years and satellite imagery shows clear signs of continuing production.[99] The Packchon milling facility that was reported to the IAEA appears to have shut down at some point in the mid-1990s.[100] The fourth facility reported to the IAEA, the Wolbisan mine, has never been reliably identified, although it appears that the mine is also known as Sunchon. It is believed that this mine has been depleted.[101]

Since uranium ore can be mined as a byproduct associated with other minerals, it is difficult to identify all uranium-producing mines using satellite images alone. Milling facilities normally have a more distinct signature, but even in this case the detection of uranium processing can be challenging without access to the site. More advanced uranium extraction technologies, such as in situ leaching, would be especially difficult to detect. However, it appears that the Democratic People's Republic of Korea does not employ these technologies at this time.

While it is certainly possible that the State extracts uranium at the facilities outside of Pyongsan, that site is probably responsible for a significant portion of natural uranium produced today. The depleted mines and shut-down milling facilities, like the one in Pakchon, most likely contributed to uranium production in the past. An estimate of the cumulative capacity of the mining complex suggests that by the end of 2018 the Democratic People's Republic of Korea may have extracted from 200,000 to 1,000,000 tonnes of uranium ore for internal consumption.[102] The lower estimate assumes operation of two mines of the size of Pyongsan; the higher estimate assumes that the extraction capacity is roughly double of that and that all mines operated closer to their maximum capacity. The amount of natural uranium produced depends on the uranium content of the ore, which introduces an additional uncertainty. Recent analysis based on geological data suggests that the uranium content is most likely in the range of 0.03–0.2% (weight per cent of uranium).[103] Adjusting for inefficiencies in the milling process, this would translate into an es-

96 "Application of Safeguards in the Democratic People's Republic of Korea", IAEA document GOV/2011/53-GC(55)/24, 2 September 2011, para. 28, https://www.iaea.org/sites/default/files/gc/gc55-24_en.pdf.

97 David F. von Hippel, "Methods for Refining Estimates of Cumulative DRPK [sic] Uranium Production", *Journal for Peace and Nuclear Disarmament*, vol. 2, no. 2, 2019, pp. 555–585, https://doi.org/10.1080/25751654.2019.1660522.

98 Sulgiye Park et al., "Geologic Analysis of the Democratic People's Republic of Korea's Uranium Resources and Mines", *Science & Global Security*, vol. 28, no. 2, 2020, https://doi.org/10.1080/08929882.2020.1789275.

99 Jeffrey Lewis, "Recent Imagery Suggests Increased Uranium Production in North Korea", 38 North, 12 August 2015, https://www.38north.org/2015/08/jlewis081215/.

100 Joseph Bermudez and Victor Cha, "Pakchon Uranium Concentrate Pilot Plant", Beyond Parallel, 21 August 2019, https://beyondparallel.csis.org/pakchon-uranium-concentrate-pilot-plant/.

101 Sulgiye Park et al., "Geologic Analysis of the Democratic People's Republic of Korea's Uranium Resources and Mines", *Science & Global Security*, vol. 28, no. 2, 2020, https://doi.org/10.1080/08929882.2020.1789275.

102 David F. von Hippel, "Methods for Refining Estimates of Cumulative DRPK [sic] Uranium Production", *Journal for Peace and Nuclear Disarmament*, vol. 2, no. 2, 2019, p. 582, https://doi.org/10.1080/25751654.2019.1660522.

103 Sulgiye Park et al., "Geologic Analysis of the Democratic People's Republic of Korea's Uranium Resources and Mines", *Science & Global Security*, vol. 28, no. 2, 2020, https://doi.org/10.1080/08929882.2020.1789275.

timate of between 280 and 1,600 tonnes of natural uranium produced by the end of 2018.[104] If one assumes that the upgraded Pyongsan complex is the only mining and milling facility that is operating today, it could probably produce about 50 tonnes of natural uranium annually.

Even though these estimates are rather uncertain, they provide an order-of-magnitude picture of potential uranium production. They should be compared with the estimated uranium demand. The plutonium production programme required about 300 tonnes of natural uranium, and the enrichment programme may have consumed from 125 to 255 tonnes of the material. The annual consumption of natural uranium required to maintain the nuclear programme in its current configuration is about 40–60 tonnes of natural uranium or 25,000–40,000 tonnes of uranium-bearing ore. This would correspond to a facility similar to the Pyongsan Uranium Concentrate Plant.

104 The assumptions about losses and efficiency are taken from David F. von Hippel, "Methods for Refining Estimates of Cumulative DRPK [sic] Uranium Production", *Journal for Peace and Nuclear Disarmament,* vol. 2, no. 2, 2019, p. 582, https://doi.org/10.1080/25751654.2019.1660522. His work, however, assumes that the uranium content of the ore could be as high as 0.9%, leading to the estimated amount of natural uranium in the range of 213–6,970 tonnes.

Progress towards denuclearizing the Korean Peninsula critically depends on finding a way to constrain and roll back the nuclear programme of the Democratic People's Republic of Korea. A freeze on its fissile material production would be the first essential step, provided that it can be made effectively verifiable. This requirement presents a significant technical as well as political challenge. This study proposes an arrangement for a verified freeze of fissile material production through a new mechanism to verify the suspension of all production activities in the early stages of the denuclearization process. It would also provide a mechanism for building confidence and trust and create a path to expanding the verification programme. In the longer run, this freeze verification arrangement would ensure that all material, military as well as civilian, will be accounted for and placed under appropriate safeguards.

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