MODELLING NORTH KOREA'S FISSILE MATERIAL PRODUCTION TO SUPPORT NEGOTIATIONS AND VERIFICATION

G. E. Christopher (grant.christopher@vertic.org)
The Verification, Research, Training and Information Centre (VERTIC)
London, United Kingdom

Abstract

A major challenge for the international community is negotiating a nuclear agreement with North Korea that results in its verifiable disarmament. An eventual disarmament process will require knowledge of North Korean fissile material inventories and associated facilities to compare with those offered in negotiations and any initial declarations in a resulting agreement. Open-source analyses since the inception of the North Korean nuclear programme have provided significant insight into DPRK fissile material production capabilities. Yet, outside intelligence communities, the full extent of DRPK fissile material production is relatively unknown, particularly for highly enriched uranium production. Using a new open-source analysis methodology, spanning the full fuel cycle, we develop a model that provides new boundaries on estimated fissile material inventories based on known and inferred facilities. The model uses probability distributions developed using open-source analysis that are input into a fuel cycle simulation built in the UK National Nuclear Laboratory's Orion software. Such an analysis can provide stakeholders without access to advanced national technical means with the best information possible to support negotiations and verification of the North Korean nuclear programme.

1. INTRODUCTION

The North Korean nuclear arsenal continues to be a major challenge to the international community. After North Korea's first nuclear test in 2006, the United Nations Security Council (UNSC) unanimously agreed resolution 1718, demanding that the DPRK return to the nuclear nonproliferation treaty, suspend its ballistic missile programme and abandon its nuclear programme in a 'complete, verifiable and irreversible manner' [1]. Later UNSC resolutions, following additional nuclear and ballistic missile tests, have adopted similar language [2-6]. Yet, decades of sanctions and summits have yielded no sustainable denuclearisation in North Korea [7]. As a result, in less than four years, North Korea will enter its third decade as a nuclear power within touching distance of thermonuclear weapons, intercontinental ballistic missiles, multiple independent re-entry vehicles (MIRVs), mobile land-based delivery platforms and a sea-based delivery system.[1]

The picture for a verifiable dismantlement of the North Korean nuclear programme is bleak. But, an opportunity for a freeze or rollback may appear if the international community, and particularly the United States, is prepared to review its engagement and negotiation strategy [8-10].

Past negotiations and agreements collapsed due to irreconcilable differences between the United States and North Korea, in part due to undeclared North Korean activities. The collapse of the Agreed Framework is due to both prior opposition in the G. W. Bush administration coupled with an assessment by the United States intelligence community of an secret enrichment programme [11]. In 2019, the Hanoi summit produced no agreement, despite North Korea offering to dismantle Yongbyon [12], with the existence of other facilities not included in any agreement thought to be a significant factor. In both these cases, withholding the full extent of fissile material production facilities scuppered a long-term agreement.

While there is a significant information asymmetry between those inside and outside intelligence communities, there is a considerable understanding of the North Korean nuclear programme in the public domain. We know North Korea possesses enrichment, reprocessing and weaponization capabilities and where these activities occur [13, 14]. What is unknown is the full extent of fissile

[1] There is disagreement among analysts if DPRK ICBMs can survive re-entry or they have yet demonstrated the capability to mount a nuclear weapon on an ICBM.

material production. In particular, North Korea is thought to have additional clandestine facilities related to highly enriched uranium (HEU) production [15].

Much of what is known (outside intelligence communities) about the centrifuge programme is based on the 2010 visit by the Los Alamos delegation to the newly built centrifuge enrichment plant at Yongbyon [16], but overall the extent of the enrichment programme is unknown. Comparably, the plutonium production at from the 5MWe reactor at Yongbyon is relatively constrained, although forensic 'nuclear archaeology' techniques would be required to answer questions about prior activities if an agreement was reached [17]. Moreover, the DPRK's production and stockpile of yellowcake, the raw material for fissile material production, is understudied.

To increase the understanding of DPRK fissile material production we present a new model, based on both new and existing open source analyses. This new model has two main aims: to model the DPRK fuel cycle as a system with trade-offs for yellowcake between Pu and HEU production pathways; and to permit multiple potential fissile material estimates that are consistent with open sources. Such a model can provide additional understanding of the DPRK nuclear programme for all stakeholders in a negotiated solution with North Korea. This paper introduces that model, but a more detailed explanation for this model and additional user features will be available in the coming months at *vertic.org/programmes/vm/dprk*.

To capture the complexity of all the possible different DPRK fissile material production estimates, that are consistent with open sources, we use a Monte Carlo method and the Orion modelling tool, developed by the UK National Nuclear Laboratory. The model, methodology, and selected results are described in the following sections.

2. KNOWN DPRK FISSILE MATERIAL PRODUCTION FACILITIES

Known DPRK fissile material production facilities are concentrated at two main sites: Yongbyon nuclear complex and the Pyongsan mine and mill complex. The nuclear complex at Yongbyon includes sites for conversion, enrichment, fuel fabrication, the 5 MWe Magnox reactor, the IRT reactor, the incomplete Experimental Light Water Reactor (ELWR), the incomplete 50 MW reactor and reprocessing at the radiochemical laboratory (RCL). Three additional facilities are confirmed or suspected to be involved in past or present North Korean fissile material production: Sunchon/Wolbisan mine, Pakchon mill and Kangson, which is suspected to be related to the gas centrifuge enrichment programme.

2.1. Mining

There are two declared mines in the DPRK: Sunchon/Wolbisan and Pyongsan. The Pyongsan mine is co-located with a mill, and both have been operational since the early 1990s. The Sunchon/Wolbisan mine's location is not known in open sources but was the supply mine to the Pakchon mill, a converted pilot uranium mill that operated between 1982-1992. Based on a Warsaw pact cable from 1979 the ore grade at the Suncheon mine is inferred to be 0.086% [18].

While there are only two identified uranium mines, there are dozens of candidate mines that could serve as additional domestic sources of uranium ore. David Von Hippel produced cumulative estimates of fissile material production based on both known mines and known uses based on candidate mines [19, 20]. Analysis by CNS, under this project, of 19 suspected mines and deposits, concluded that only the Pyongsan and Sunchon/Wolbisan mines could be assessed as mines linked with uranium. The analysis was based on visible signatures from overhead imagery and other open sources. Moreover, in this analysis several mines and candidate sites were assessed to be the same facility with different names [21].

The ore mined at Pyongsan, and its grade, has been the result of considerable discussions, with no conclusive answers. An IAEA visit prior to the Agreed Framework declared that the material mined was anthracite coal, with nickel and vanadium by-products [22]. With this assumption, the ore grade is best modelled via the Hungarian cables to be 0.26% [18]. Alternatively, Park et al., using technical geological methods, have inferred that the ore mined at Pyongsan is black shale, which places the ore grade to be lower at 0.03% [23, 24].

2.2. Milling

Pakchon is a former phosphate/rare earth mill that was converted to a uranium mill. It operated from 1982-1992 as a pilot plant for yellowcake production. The only estimate of total production from open sources is 210 tU [25].

Operational since 1990, Pyongsan mill, co-located with the mine, is the only still operational mill in North Korea since after the Pakchon mill was ceased operation in the mid-1990s [25].

Production estimates for Pyongsan mill have been produced by several groups. David von Hippel at Nautilus produced an analysis with both 'top-down' and 'bottom-up' assessments of DPRK uranium ore inventories [19, 20]. The top down assessment of 200-800 tU (with a central estimate of 400 tU) provide the ore required to produce the DPRK's fissile material estimates by Albright [13] and Hecker [26]. The bottom-up assessment takes confirmed and assumed mines, at ore grades provided in the open sources to produce an overall inventory and ranges from 200-7000 tU, with a central estimate of 800 tU. An estimate based on Counter Current Decanter (CCD) size yields an estimate of 273-886 tU3O8 annual production [27], and an estimate based the tailing pond size changes over time produces 7-497 tU3O8. A detailed study by Park et al., assuming ore processed from black shale, estimates annual production as 90 tU [24].

In a 1992 site visit by the IAEA, Pyongsan is described as a nickel, vanadium and uranium mill with anthracite coal as the raw input material for the mill [18]. David Schmerler provided a new explanation of the process flow at Pyongsan mill consistent with the facility processing coal [28]. In this analysis, the mill is a uranium mill with vanadium and nickel by-products where uranium is extracted from coal-ash after production in a rotating kiln. One of the insights of this analysis is that the area covered by the Pyongsan mill site very large relative to other uranium mills with similar production estimates. Understanding the site as a multi-material facility we estimate annual production as ~70-110 tU per year.

2.3. Conversion

All known conversion facilities are located at the Yongbyon nuclear complex. Prior to the requirement of UF6 for enrichment, the production line was thought to include U3O8 to UF4 conversion[2], hydrofluoric acid production and UF4 to U-metal conversion facilities [14, 29]. Prior to 2009, the conversion line was modified and is now thought to include UF4 to UF6 conversion and reconversion to serve the Experimental Light Water Reactor and the new enrichment plant [30].

However, it is unclear how any UF6 could be produced at an earlier date using these facilities, which would be required either to supply UF6 to Libya or enrichment at another site such as Kangson [30]. As such, North Korea may operate additional conversion plants at unknown locations [30].

For the fuel cycle model, the availability of conversion facilities does not provide a constraint on the model, but can provide contextual information for other stages of the fuel cycle. Moreover, loss fractions are kept at the same rate for the same process, even during the reported switch from wet to dry UF4 conversion.[3]

2.4. Enrichment

Much is still unknown about the extent of the DPRK enrichment programme. Prior to the construction of the gas centrifuge enrichment plant at Yongbyon, the main open source for the existence of a DPRK enrichment programme was a US government assessment that led to the collapse of the Agreed Framework in 2002 and that there was support for an assessment in the US Government that HEU was detected on materials taken out of North Korea in 2006-2007 [13]. No associated facilities were

[2] Via UO3->UO2->UF4, using a wet process.

[3] Loss fractions in efficient processes are assumed to be 2-3% from Caiado, Beddingfield, Ferrada, Ladd-Lively, Marzo, Palhares, Diaz and Grund, 'Model of a Generic Natural Uranium Conversion Plant-Suggested Measures to Strengthen International Safeguards', 2009, . Here we assume 5% including fuel fabrication. After reconversion, and conversion to metal, HEU is assumed to have an overall loss of 10%.

positively identified until the 2010 delegation visit to the uranium enrichment workshop (UEW) [16]. Satellite imagery showed that this facility approximately doubled in size in 2013-2014 [14]. In 2020, the Center for Nonproliferation Studies, in collaboration with Ankit Panda, identified the Kangson site as associated with the gas centrifuge enrichment programme [15].

The technology shown to Sig Hecker in the 2010 visit was consistent with a P2-type centrifuge, acquired via the A. Q. Khan network. To estimate the extent of the DPRK enrichment programme analysts have developed two types of model. In the first, the UEW at Yongbyon is the largest centrifuge facility and only a pilot plant exists alongside this. In this scenario, Albright takes Hecker's estimate of 2000 P2-type centrifuges observed in the UEW and assumes a four-stage enrichment process and operational challenges with the centrifuges. This reduces a 5 SWU/centrifuge by a third for a total SWU/year for the plant of 6500 from 2010 to 2015 and 10,000-13,000 from 2016 [13].

In the second scenario, there is a second large clandestine centrifuge facility that may be Kangson or some facility not yet identified in open sources. Albright in this scenario assumes the clandestine facility becomes operational from 2005-2010 with a similar size to the UEW for total SWU/year of 26,000 [13]. Hecker, under this scenario, assumes a pilot plant with two cascades (660 centrifuges) and a SWU/centrifuge of 4. The UEW then has 8000 SWU/year from 2010-2015 and 16,000 SWU/year from 2016 onwards. A clandestine facility is constructed in 2013-2014 and expanded in 2017-2018 for a total 35,000 SWU/year. Hecker's analysis is based on North Korea's annual production capability of rotors, with two flow-forming machine between them capable of producing 1500 P2 rotors/year.[4]

2.5. Plutonium breeding in reactors

The 5 MWe reactor is a Magnox-type reactor located at Yongbyon and has been operating intermittently since 1986 [32, 33]. Other than the IRT, it is the only reactor North Korea has operated capable of producing plutonium. The reactor takes 50 tU metallic uranium fuel[5] and although was designed to operate at 25 MWt it has operated typically below 20 MWt [33].

The IAEA describes the reactor as having six operational cycles, with the first cycle consisting of operations between 1986-1994 and the sixth cycle having commenced in July 2021 [32]. In the first operational cycle there is still uncertainty about when loading and unloading occurred, how much fuel was unloaded, and exactly how much fuel was reprocessed [33]. In the following cycles typically a full fuel load of 50 tU is assumed to be in the reactor for 2-3 years, depending on the operational cycle.

The reactor has proven to be remarkably resilient. After the Agreed Framework, the reactor was able to restart with fewer difficulties than anticipated, and after the cooling tower was demolished in 2008 the reactor was able to restart in 2013 with a new cooling system. Magnox-type reactors have known issues such as warping of the graphite moderator, which are expected to degrade reactor performance over time.

Based on the observed operational history, and some declared information from visits and prior inspections, the cumulative estimated plutonium production for the reactor ranges from 25-48 kg by Sig Hecker [34] and 23-37 kg (prior to the latest reprocessing campaign) by David Albright [13].

2.6. Reprocessing

The first North Korean reprocessing that we are aware of took place in 1975 with fuel taken from the IRT reprocessed in a hot cell in the nearby Isotope Production Laboratory [33]. The radiochemical laboratory (RCL) at Yongbyon is the main facility at Yongbyon, with the first process line tested in 1990 and the second completed in 1994 [35, 32]. This plant uses an PUREX process and has an

[4] In this analysis the rotor is the assumed to be the choke-point centrifuge component and other components such as bellows, bearings and magnets are unconstrained relative to centrifuges.

[5] With 55.5 tU needed assuming 10% losses in fuel fabrication

estimate capacity of 110 tU (or 220-250 tU depending on the source) [35]. This is far in excess of the required capacity for the 5 MWe Magnox-type reactor of 50 tU/year.

There is still uncertainty about the first reprocessing campaigns prior to the Agreed Framework [32] that could be resolved with techniques such as nuclear archaeology [17]. The fuel unloaded and stored in the Magnox storage pond in 1994 was reprocessed in 2003 [32]. The corrosion of this fuel likely led to significant material losses in the decladding stage for this fuel load. This is likely the largest loss stage in reprocessing, with very high efficiency possible typically using the PUREX process.[6] The overall losses from reprocessing, with most of the losses occurring at the decladding stage and some liquid stage losses of Pu and reprocessed U to waste streams are modelled at 15%. Subsequent fuel loads were reprocessed sooner after discharge from the reactor reducing these losses but are modelled currently with the same loss rate.

2.7. Tritium Production

DPRK tritium production could occur directly in the IRT reactor or 5 MWe reactor [36]. In the Monte Carlo model, the option of tritium production allocates the UEW to produce a batch of 50 tU enriched to 0.95%. While the UEW is enriching to this level it no longer is allocated to produce HEU. The model then assumes 17g/year of tritium is produced.[7]

The prime candidate reactor campaigns for tritium breeding are the post-Six Party talks reactor campaigns, beginning in August 2013. Pilot tritium breeding may have occurred in prior reactor campaigns, but as tritium has a 12.3 half-life, 5.5% will decay away per year, implying that tritium would have been most efficient to produce closer to a planned test.[8]

2.8. Additional known facilities

The IRT reactor and the ELWR are both located at the Yongbyon nuclear complex. The ELWR is currently not operational, but fuel was thought to be fabricated for this reactor in the last decade. Sig Hecker has the facility requiring 4 tU, enriched to 3.5% [14].[9]

The IRT was built in the 1960s and was supplied with Soviet-manufactured fuel until recently. The exact uses of the reactor are not known and if the DPRK has manufactured HEU fuel for the reactor since the 1987 upgrade to 8 MWt, which now uses a mixed core load including 80% HEU [14].

3. A NEW FUEL CYCLE MODEL

The previous section describes the key facilities and inputs for a North Korean fuel cycle model. In this section we describe a new model of the cumulative DPRK fissile material production using those inputs.

3.1. Monte Carlo

Any DPRK fissile material estimate requires a large number of parameters, including operational date ranges, annual production estimates, the number of operating gas centrifuges and thermal power of the 5 MWe reactor. To capture the uncertainties and possible variance in the fissile material estimate across such a large number of parameters a Monte Carlo model is used. Here, each input parameter is assigned a distribution which is then independently randomly sampled for each Monte Carlo run.

---

[6] Based on private remarks at a 2019 workshop.

[7] Under the reactor model we work with this addition is ‘by hand’. Similarly, the consequent loss in Pu production is done by hand.

[8] If 6g tritium were produced in the 2005-2007 reactor campaign (assuming 3g/year from natural U enrichment), about 3.5g would remain for the January 2016 test. This would be sufficient under the assumptions on tritium requirements we have made, but at the loss of nearly half the tritium produced.

[9] Losses for the fuel fabrication and conversion processes are estimated at 10% for the ELWR.

Depending on each modelling scenario, between 50-70 parameters are used. For each scenario, a sufficient number of models are run to explore the parameter space. The input distributions chosen are appropriate for the parameter and are typically top hat or gaussian distributions. The exceptions to this are the load factors for the reactor, which are taken from binned Magnox operational data and either/or choices in the modelling, such as the model of centrifuge used, which are selected based on a prior probability distribution.

3.2. Nuclear modelling with Orion

The nuclear fuel cycle modelling is performed with Orion. Orion is fuel cycle scenario modelling software designed and maintained by the UK's National Nuclear Laboratory (NNL) [37-39]. The software individually tracks over 500 isotopes through enrichment, irradiation and reprocessing. The software uses a graphical user interface (GUI) which can be populated with the required nuclear facilities and parameters as shown in Figure 1.

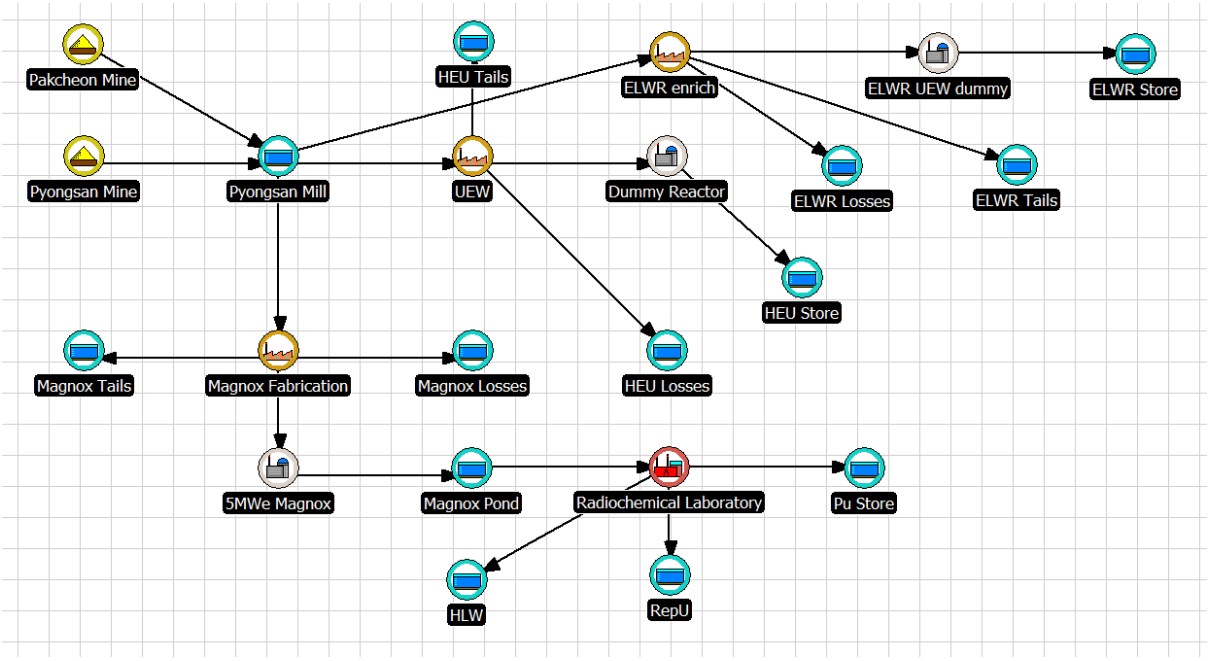

Figure 1: An Orion file showing the DPRK fuel cycle.

To perform this analysis and adapt Orion for Monte Carlo modelling, VERTIC collaborated with the Orion design team to add a number of custom features for this analysis. VERTIC then built a wraparound package to generate, run and read scenarios populated with Monte Carlo generated data, each using an Orion template scenario file.

The software models the physics processes in the fuel cycle for enrichment and reactors.[10] All other processes, such as reprocessing are allocated in the GUI individually by isotope. Reactor loading is done in 'explicit' mode which allows specific masses of fuel to be added with explicit loading and unloading dates.[11] Enrichment is performed by solution of the centrifuge equation with the assumption that there is always SWU capacity to enrich the fuel. Enrichment is always assumed to feed a reactor and this is a requirement in the software. To provide enriched fuel the available SWU is modelled by VERTIC in the wraparound code and the resulting product mass is then 'loaded' into a dummy reactor for Orion to be able to conduct the enrichment.

[10] The reactor Magnox file for the 5 MWe was generated and validated by NNL.

[11] Other Orion modes are designed to automatically withdraw fuel to model a complex fuel cycle over the lifetime of a reactor.

4. SCENARIOS AND BASELINE RESULTS

The model works across various scenarios to the provide fissile material flow estimates for the DPRK nuclear programme, beginning in 1978 and running to the end of 2022. The model tracks uranium from the yellowcake stage. During the model the uranium can end up in one of seven places:

1. HEU production
2. Enrichment tails
3. Transmuted for Pu production
4. Transmuted into HLW
5. Unrecoverable and recoverable material loss
6. ELWR fuel
7. Stockpiles of uranium in various forms (yellowcake, UO3, UF6 etc.).

The quantity of Pu, HEU and tritium produced can vary greatly based on model input assumptions and broader assumptions about the state of DPRK fissile material production depending on the chosen scenario below.

4.1. Scenarios

A scenario reflects a broad set of assumptions in what is known about the DPRK fuel cycle while still being consistent with open sources. The key unknowns are: annual yellowcake production, the extent of the gas centrifuge programme and finally tritium production. Within these assumptions we are currently simulating the following scenarios:

1. Baseline enrichment and reactor performance based on observed facilities only.
2. Exploring maximum HEU production based on a) increasing the tails assay to consume more of the available yellowcake stockpile b) 2nd large centrifuge enrichment plant and c) improvements to the centrifuge model.
3. Large-scale tritium production that includes the use of enriched uranium in the 5 MWe reactor.
4. Minimal available yellowcake, constraining the HEU production.[12]

4.2. Results and next steps

The baseline model predicts, at the end of 2022, a cumulative stockpile of highly enriched uranium of ~650-950 kg and a plutonium inventory of 53-65 kg. Additional model estimates, and any updates to the baseline estimate, will be updated in the coming months at the dedicated site maintained at *vertic.org/programmes/vm/dprk*. This will be updated with detailed explanations of the model, with its inputs and results. The scenarios described here will be continued to refined and updated to reflect new insights, scholarship and developments into 2023.

While modelling the fuel cycle together in a single system, with careful treatment of uncertainty can show bounds on the observed fuel cycle, the greater challenge is the understanding of clandestine facilities. The largest uncertainty in the model is related to the overall SWU/year available to the DPRK.

The model is designed to be flexible and to be able to work with differing assumptions that are consistent with open sources. For future negotiations, and verification of any North Korean agreement, the model can be adapted and updated with new data, sources and measurements.

ACKNOWLEDGEMENTS

[12] We note that this is inconsistent with most reasonable assessments of available yellowcake to the DPRK, but may represent more difficulties in mining, milling and converting uranium than we have been estimating.

This project was funded by the Government of Canada. We would also like to acknowledge and thank our project partners at the Royal United Services Institute (RUSI) and the Center for Nonproliferation Studies (CNS). Finally, we would like to thank the United Kingdom National Nuclear Laboratory for their support and permission for use of Orion software.

REFERENCES

[1] United Nations Security Council, S/RES/1718 (2006).
[2] United Nations Security Council, S/RES/1874 (2009).
[3] United Nations Security Council, S/RES/2087 (2013).
[4] United Nations Security Council, S/RES/2270 (2016).
[5] United Nations Security Council, S/RES/2371 (2017).
[6] United Nations Security Council, S/RES/2375 (2017).
[7] CRS *Nuclear Negotiations with North Korea* [Online]. Congressional Research Service. Available: https://crsreports.congress.gov/product/pdf/R/R45033?source=GovD [Last Updated 2021].
[8] IISS *Reengaging North Korea on Its Nuclear and Ballistic Missile Capabilities* [Online]. International Institute for Strategic Studies. Available: https://www.iiss.org/events/2021/10/reengaging-north-korea [Last Updated 2021].
[9] TOWN, J. *Challenges of Negotiating with North Korea* [Online]. Stimson Center. Available: https://www.stimson.org/2021/biden-review-challenges-of-negotiating-with-north-korea/ [Last Updated 2021].
[10] YUN, J. & F. AUM *A practical approach to North Korea for the next US president* [Online]. Bulletin of the Atomic Scientists. Available: https://thebulletin.org/2020/10/a-practical-approach-to-north-korea-for-the-next-us-president/ [Last Updated 2021].
[11] DAVENPORT, K. *The U.S.-North Korean Agreed Framework at a Glance* [Online]. Arms Control Association. Available: https://www.armscontrol.org/factsheets/agreedframework [Last Updated 2019].
[12] BBC *Trump-Kim summit breaks down after North Korea demands end to sanctions* [Online]. Available: https://www.bbc.co.uk/news/world-asia-47398974 [Last Updated 2019].
[13] ALBRIGHT, D. *North Korea's Nuclear Capabilities: A Fresh Look* [Online]. Institute for Science and International Security. Available: https://isis-online.org/isis-reports/detail/north-koreas-nuclear-capabilities-a-fresh-look-power-point-slides/10 [Last Updated 2017].
[14] BRAUN, C., S. HECKER, C. LAWRENCE & P. PAPADIAMANTIS. *North Korean Nuclear Facilities After the Agreed Framework* [Online]. The Center for International Security and Cooperation. 2016.
[15] PANDA, A. *Exclusive: Revealing Kangson, North Korea's First Covert Uranium Enrichment Site* [Online]. The Diplomat. Available: https://thediplomat.com/2018/07/exclusive-revealing-kangson-north-koreas-first-covert-uranium-enrichment-site/ [Last Updated 2018].
[16] DAY, C. *Visiting North Korea: Q&A with Siegfried Hecker* [Online]. Physics Today. Available: https://physicstoday.scitation.org/do/10.1063/pt.4.0324/full/ [Last Updated 2011].
[17] LANVERSIN, J. D. T. D. & M. KÜTT, Verifying North Korea's Plutonium Production with Nuclear Archaeology. *Science & Global Security*, 29 (2021) 145-166.
[18] SZABO, F. *TELEGRAM, EMBASSY OF HUNGARY IN NORTH KOREA TO THE HUNGARIAN FOREIGN MINISTRY* [Online]. Wilson Center. Available: https://digitalarchive.wilsoncenter.org/document/110133 [Last Updated 1979].
[19] HIPPEL, D. V. *Methods for Refining Estimates of Cumulative DRPK Uranium Production* [Online]. Nautilus Institute. Available: https://nautilus.org/napsnet/napsnet-special-reports/methods-for-refining-estimates-of-cumulative-dprk-uranium-production/ [Last Updated 2019].
[20] VON HIPPEL, D. F., Methods for Refining Estimates of Cumulative DRPK Uranium Production. *Journal for Peace and Nuclear Disarmament*, 2 (2019) 555-585.
[21] DILL, C., M. CROY, D. SCHMERLER & J. WITHORNE 2019. Using Remote Sensing Technologies to Identify Uranium Mines & Mills in the DPRK (Unpublished Work).
[22] IAEA *IAEA footage of Director General Hans Blix Touring North Korean Nuclear Sites in 1992* [Online]. YouTube. Available: https://www.youtube.com/watch?v=qfr0PEf60xE [Last Updated 1992].
[23] PARK, S., et al., Geologic Analysis of the Democratic People's Republic of Korea's Uranium Resources and Mines. *Science & Global Security*, 28 (2020) 80-109.
[24] PARK, S., M. TERRY, A. PUCCIONI & R. C. EWING, Assessing Uranium Ore Processing Activities Using Satellite Imagery at Pyongsan in the Democratic People's Republic of Korea. *Science & Global Security*, 29 (2021) 111-144.
[25] JR., J. S. B. & V. CHA *Pakchon Uranium Concentrate Pilot Plant* [Online]. Center for Strategic and International Studies. Available: https://beyondparallel.csis.org/pakchon-uranium-concentrate-pilot-plant/ [Last Updated 2019].

[26] HECKER, S. S., C. BRAUN & C. LAWRENCE, North Korea's Stockpiles of Fissile Material. *Korea Observer*, 47 (2016) 721.
[27] GRACE LIU, et al. *OP #44: Eyes on U: Opportunities, Challenges, and Limits of Remote Sensing for Monitoring Uranium Mining and Milling* [Online]. Center for Nonproliferation Studies. Available: https://nonproliferation.org/op-44-eyes-on-u-opportunities-challenges-and-limits-of-remote-sensing-for-monitoring-uranium-mining-and-milling/ [Last Updated 2019].
[28] SCHMERLER, D. *A SATELLITE IMAGERY REVIEW OF THE PYONGSAN URANIUM MILL* [Online]. Armscontrolwonk.com. Available: https://www.armscontrolwonk.com/archive/1209625/pyongsan-uranium-mill/ [Last Updated 2020].
[29] WITHORNE, J. *NORTH KOREAN URANIUM CONVERSION: HISTORY AND PROCESS, PART 1* [Online]. Available: https://www.armscontrolwonk.com/archive/1212071/north-korean-uranium-conversion-history-and-process-part-1/ [Last Updated 2021].
[30] WITHORNE, J. *NORTH KOREA'S URANIUM CONVERSION: THE HISTORY AND PROCESS, PART 2* [Online]. Available: https://www.armscontrolwonk.com/archive/1212202/north-koreas-uranium-conversion-the-history-and-process-part-2/ [Last Updated 2021].
[31] CAIADO, A. R., et al., Model of a Generic Natural Uranium Conversion Plant-Suggested Measures to Strengthen International Safeguards. *Oak Ridge National Laboratory, Oak Ridge, TN ORNL/TM-2008/195,* (2009)
[32] IAEA. *Application of Safeguards in the Democratic People's Republic of Korea* [Online]. GOV2022/40-GC(66)/16 Available: https://www.iaea.org/sites/default/files/gc/gc66-16.pdf 2022.
[33] ALBRIGHT, D. & K. O'NEILL 2000. *Solving the North Korean nuclear puzzle*, Institute for science and international security Washington, DC.
[34] HECKER, S. *Estimating North Korea's Nuclear Stockpiles: An Interview With Siegfried Hecker* [Online]. 38 North. Available: https://www.38north.org/2021/04/estimating-north-koreas-nuclear-stockpiles-an-interview-with-siegfried-hecker/ [Last Updated 2021].
[35] JOOHO, W. & G. T. BALDWIN. *Dismantlement and radioactive waste management of DPRK nuclear facilities* [Online]. SNL-A (Sandia National Laboratories, Albuquerque, NM). 2005.
[36] KIM, M. S., S. J. LEE & S. Y. CHANG. DPRK's 4th Nuclear Test and its Tritium Production. Proceedings of the KNS 2016 Spring Meeting, 2016 Korea, Republic of. KNS, 1CD-ROM.
[37] DAVIDSON, E. E., B. R. BETZLER, R. GREGG & A. WORRALL. *Modeling a Fast Molten Salt Reactor with ORION* [Online]. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States). 2018.
[38] PETERSON, J., et al., Generating Cross Sections for ORION Fuel Cycle Models. *Proc. PHYSOR 2016,* (2016) 1-5.
[39] DAVIDSON, E. E., J. L. PETERSON-DROOGH, A. WORRALL & R. GREGG. *A US-UK Collaboration on Fuel Cycle Assessment* [Online]. Oak Ridge National Lab.(ORNL), Oak Ridge, TN (United States). 2017.