NORTH KOREAN FISSILE MATERIAL: A NEW MODEL

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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 program have provided significant insight into DPRK (Democratic People s Republic of Korea) fissile material production capabilities. Yet, outside intelligence communities, the full extent of DRPK fissile material production is unknown, particularly for highly enriched uranium production. Using a new open-source analysis methodology, spanning the full fuel cycle, we describe 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. The model, its results, and tools for analysts and policy makers to explore the outputs will be presented. Such an analysis can provide a broad range of stakeholders without access to advanced national technical means with the best information possible to support negotiations and verification of the North Korean nuclear program.

1. INTRODUCTION

The North Korean nuclear arsenal continues to be a major challenge to the international community. From the Democratic People's Republic of North Korea's (DPRK) first nuclear test in 2006 it has continued to expand its nuclear arsenal and delivery systems. Throughout the expansion of the North Korean nuclear programme the United Nations Security Council (UNSC) has demanded the DPRK returns to the Nuclear Nonproliferation Treaty, ceases nuclear testing and a suspends its ballistic missile programme [1-6]. Underpinning the nuclear programme the fissile material production complex which has been able supply enough material for at least six nuclear tests and a presumed weapons stockpile.

Results of nuclear negotiations between the United States and North Korea have had some success in DPRK temporarily slowing or freezing fissile material build-up, but ultimately they have resulted in an embedded nuclear programme that the DPRK will not trade away [7]. The Agreed Framework was the longest-lasting settlement, but collapsed due to *a priori* opposition in the G.W. Bush administration and an assessment by the United States intelligence community of an undeclared enrichment programme [8]. The Six Party talks paused or slowed fissile material production, but collapsed in 2009 [9, 10]. The most recent round of negotiations: the 2018-2019 Leader Summits in Singapore and Vietnam resulted in no agreement due to irreconcilable differences in US and DPRK negotiating positions [10]. Reportedly, the DPRK offered dismantlement of Yongbyon nuclear complex during these negotiations [11]. The rejection by the US is thought to be due to lack of completeness – other inferred clandestine facilities would remain outside a deal. Many analysts now consider a negotiated complete verifiable disarmament of North Korea to be no longer viable, although some do not think that this should be the end of negotiations or a shift from disarmament to arms-control negotiations [12].

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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 .

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

To democratise the understanding of cumulative DPRK fissile material production we present a new model based on both existing and new open source analysis, This model uses Orion software, developed and maintained by the UK National Nuclear Laboratory (NNL), to simulate the full North Korea fuel cycle from its inception to the present day. As the model includes both plutonium and HEU pathways simultaneously, yellowcake in the model is a resource allocated between these production pathways. Such a model can provide additional understanding of the DPRK nuclear programme for all stakeholders in a negotiated solution with North Korea.[3]

2. KNOWN DPRK FISSILE MATERIAL PRODUCTION FACILITIES

Known DPRK fissile material production facilities are concentrated at Yongbyon nuclear complex. which includes facilities for uranium 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.. Three additional facilities were declared in 1992 to the IAEA: Pyongsan mine and mill, the Sunchon/Wolbisan mine and Pakchon mill. The only undeclared facility linked to the fuel cycle that has been identified is Kangson which is suspected to be related to the gas centrifuge enrichment programme[15].

2.1. Mining

In 1992, the DPRK declared two mines to the IAEA: Sunchon/Wolbisan and Pyongsan [16]. This corroborates a Warsaw pact cable from 1979 which identified two operational mines [17]. The Pyongsan mine is co-located with a mill which has been operational since the early 1990s. The Sunchon/Wolbisan mine's location is not known in open sources. This mine was thought to supply the Pakchon mill, a converted pilot uranium mill that operated between 1982-1992 [16].

In addition to the two known mines researchers have identified many additional candidate mines that could serve as additional domestic sources of uranium ore. David Von Hippel has produced a cumulative estimate of fissile material production based on both known mines and candidate mines [18, 19]. 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. This analysis is 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 [20].

The type of ore mined at Pyongsan and Pakchon, and its uranium grade, has been the result of considerable debate, 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 [21]. With this assumption, the ore grade is best modelled via the Hungarian cables to be 0.26% [17]. 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% [22, 23].

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[3] 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*.

2.2. Milling

Pakchon is a former phosphate/rare earth mill that was converted to a uranium mill [24]. It operated from 1982-1992 as a pilot plant for yellowcake production. Estimated cumulative production at the mill from open sources is 210 tU [24]. It should be noted that this was the only known operational mill to fuel the 5 MWe reactor at Yongbyon in 1986.The Pyongsan mill, co-located with a uranium mine, and is the only operational uranium mill in North Korea since after the Pakchon mill was ceased operation in 1992 [24].

Production estimates for Pyongsan mill have been produced by several authors. David von Hippel at Nautilus produced an analysis with both ‘top-down’ and ‘bottom-up’ assessments of DPRK uranium ore inventories [18, 19]. The top-down assessment of 200-800 tU (with a central estimate of 400 tU) is based on the ore required to produce the fissile material estimates by David Albright [13] and Sieg Hecker [25]. 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 a stage in the inferred uranium ore concentrate process, using a Counter Current Decanter (CCD) for solid-liquid separation yields an estimate of 273-886 tU3O8 annual production[4] [26]. 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 [23].

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 [17]. David Schmerler provided a new explanation of the process flow at Pyongsan mill consistent with the facility processing anthracite coal [27]. 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 large relative to other uranium mills with similar production estimates. Understanding the site as a multi-material facility we estimate annual production as 10-30 tU3O8 per year from 1990-1993 as a commissioning phase and 50-120 tU3O8 per year from 1994 to the present day

2.3. Conversion

All known conversion facilities are located at the Yongbyon nuclear complex. Prior to the requirement of UF6 for enrichment, the conversion line used U3O8 to UF4 conversion[5], hydrofluoric acid production and UF4 to U-metal conversion facilities [14, 28]. Prior to 2009, the conversion line was modified and is now thought to include UF4 to UF6 conversion to serve the Experimental Light Water Reactor and the new enrichment plant [29].

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 [16] or enrichment at another site such as Kangson [28-30]. As such, North Korea may operate additional conversion plants at unknown locations [29].

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 in the model for the same process, even during the reported switch from wet to dry UF4 conversion.[6]

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[4] This estimate infers that CCDs are used in this process as they are not visible. The size and number of CCDs are

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

[6] Loss fractions in efficient processes are assumed to be 2-3% from AC Raffo Caiado, 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.. Here we assume 5% including fuel fabrication. After reconversion, and conversion to metal, HEU is assumed to have an overall loss of 10%.

2.4. Enrichment

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 [32], but overall, the extent of the enrichment programme is unknown.

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. In support of early conversion and enrichment is an assessment, including by the IAEA, that natural UF6 of North Korean origin was provided to Libya prior to 2001 [16]. In addition, 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 enrichment facilities were positively identified until the 2010 delegation visit to the uranium enrichment workshop (UEW) at Yongbyon [32]. Satellite imagery shows 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 Sieg Hecker in the 2010 visit was consistent with a P2-type centrifuge, acquired via the A. Q. Khan network [14]. To estimate the extent of the DPRK enrichment programme analysts have developed two types of models. In the first, the UEW at Yongbyon is the largest centrifuge facility and only a pilot plant exists alongside this, responsible for all pre-2010 evidence of enrichment. In this scenario, Albright takes Hecker’s estimate of 2000 P2-type centrifuges observed in the UEW and assumes a four-stage enrichment process as observed in Libya [33] and operational challenges with the centrifuges that reduces a 5 SWU/centrifuge effectively 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 comparable 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 machines between them capable of producing 1500 P2 rotors/year.[7]

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 [16, 34]. 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[8] and although was designed to operate at 25 MWt it has operated typically below 20 MWt [34].

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 [16]. 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 [34]. 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 observed 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 disablement activities conducted under the Six-Party talks, including demolition of the cooling tower in 2008 the reactor was able to restart in

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[7] 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.

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

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 Hecker (in 2021) [35] and 31-35 kg up to 2016 by Albright [13]. A reactor core model by Park at al. using Hecker's operational data estimates 46.7-76.6 kg of Pu produced up to the end of the 2019 campaign [36].

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 [34]. 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 [16, 37]. This plant uses an PUREX process and has an estimate capacity of 110 tU (or 220-250 tU depending on the source) [37]. This is far more than the required capacity for the 5 MWe Magnox-type reactor of 50 tU/year. There is still uncertainty about the plutonium produced from reprocessing campaigns prior to the Agreed Framework [16] that could be resolved with techniques such as nuclear archaeology [38]. Since the Agreed Framework, the IAEA has noted five full reprocessing campaigns, in 2003, 2005, 2009, 2016 and 2021 and a shorter campaign in 2018 [16]. The post-Agreed Framework campaign in 2003 is especially notable for high corrosion of this fuel, due to being stored in the Magnox pond from 1994-2002 which is expected to lead to significant material losses in the decladding stage for this fuel load.[9] This is the largest loss stage in reprocessing, with extremely high efficiency possible typically using the PUREX process.[10] 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 [39]. 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.[11]

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.[12]

2.8. Additional known facilities

The IRT reactor and the ELWR are both located at the Yongbyon nuclear complex. The ELWR, up until the end of 2022 was not operational, but has recently been a source of renewed analysis about its

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[9] A private consultation from an expert familiar with the PUREX process estimated very high losses at the decladding stage.

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

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

[12] 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.

status of operation [40]. Fuel was thought to be fabricated for this reactor in the last decade and Sieg Hecker has the facility requiring 4 tU, enriched to 3.5% [14].[13]

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 many parameters, including operational date ranges, annual production estimates, the number of operating gas centrifuges and the thermal power of the 5 MWe reactor. To capture the uncertainties and variance in the fissile material estimate across many parameters a Monte Carlo model is used. Here, each input parameter is assigned a distribution, based on assessments of available open source data, which is then independently randomly sampled for each Monte Carlo run. Depending on each modelling scenario, between 50-70 parameters are used. For each scenario, enough 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[14] and either/or choices in the modelling, such as the model of centrifuge used, which are selected under some scenarios based on a prior probability distribution.

3.2. Nuclear modelling with Orion

The nuclear fuel cycle model uses Orion. Orion is fuel cycle scenario modelling software designed and maintained by the UK’s National Nuclear Laboratory (NNL) [41-43]. 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.

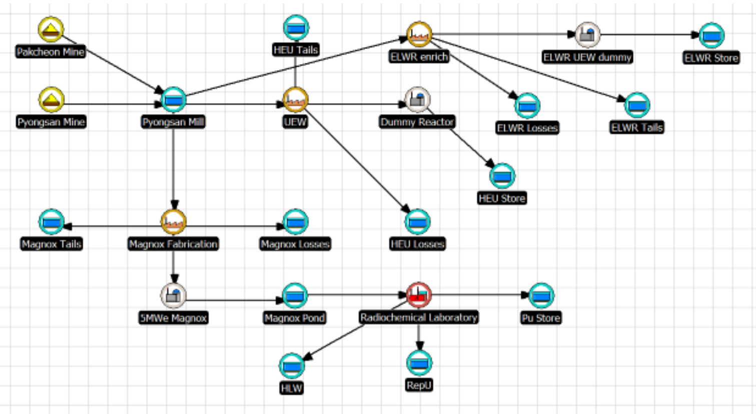

Figure 1: An Orion GUI showing the DPRK fuel cycle.

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

[14] Data is taken from the IAEA Reactor Database using data from all Magnox-type reactors.

To perform this analysis and adapt Orion for Monte Carlo modelling, VERTIC collaborated with the Orion design team to add several 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.[15] All other processes, such as reprocessing are allocated in the GUI individually by isotope. Reactor loading for this model uses 'explicit' mode which allows specific masses of fuel to be added with specified loading and unloading dates.[16] Enrichment uses the solution of the centrifuge SWU equation with the sums of value functions[17] [33],

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 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 requirements. Within these assumptions we have simulated the following scenarios:

1. Baseline enrichment and reactor performance based on observed facilities only.
2. Increased HEU production based on increasing the tails assay to consume more of the available yellowcake stockpile. Here we use a 10-year cycle of projected yellowcake stockpile and in the model the tails are permitted to increase for this 10-year period, up to tails assay 0.55 while there are available yellowcake stocks.
3. Considering the construction of a 2nd large clandestine centrifuge enrichment plant that is a similar size to the UEW enrichment plant before the UEW.
4. A 2nd large clandestine centrifuge enrichment plant, similar in size to the UEW constructed after the UEW.

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

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

[17] Orion typically operates 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.

5. Assumed improvements to the centrifuge model used for enrichment [44]. Rather than assuming no improvements to the P2-type centrifuge here the DPRK mirrors Iranian development and the expansion of the UEW at Yongbyon uses carbon fibre rotors with comparable SWU to IR-6 centrifuges.[18]
6. Tritium breeding in 5MWe reactor that reduces the available neutron flux so requires the use of 0.95% enriched uranium in the 5 MWe reactor [45].
7. Minimal available yellowcake, constraining the HEU production.[19]

4.2. Results and next steps

Results from some models are presented for HEU in Figure 2 and Pu in Figure 3. The estimated Pu production is uniform for nearly all scenarios apart from the use of the 5 MWe reactor for tritium production. Estimated HEU production is highly dependent on the choice of scenario. Production in all scenarios rises rapidly after the completion of the expansion of the UEW at Yongbyon and the model predicts annual expansion of the stockpile to be 80-150 kg/HEU per year depending on the scenario and is comparable to other estimates [46].

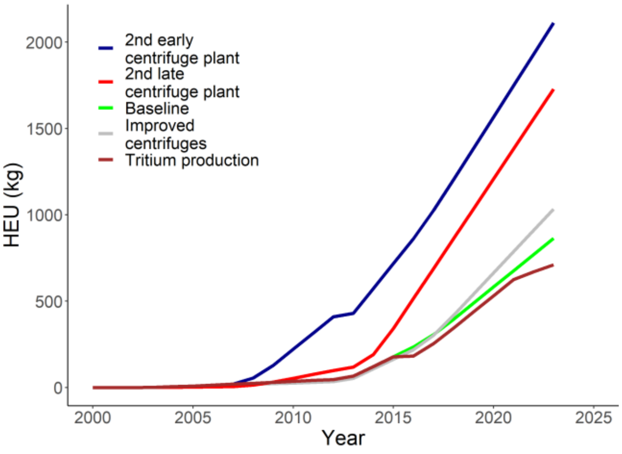

Figure 2: Cumulative HEU production from 2000-2023 from derived scenarios.

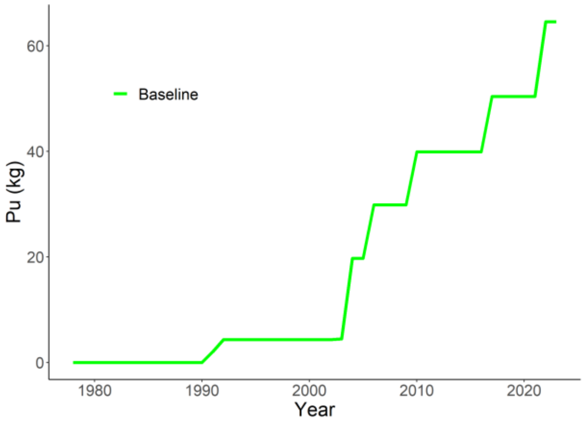

Figure 3: Cumulative separated Pu from the 5 MWe.

Modelling the fuel cycle together in a single system, with careful treatment of uncertainty can show bounds on the observed fuel cycle. Yet, the model is limited by the lack of data to adequately model fissile material production from clandestine facilities. The largest uncertainty in the model is related to

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[18] Expert elicitation has noted that this scenario lacks supporting evidence of the DPRK either importing precursor material or mastering the very difficult problem of working with carbon fibre of the required grade.

[19] 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.

the overall SWU/year available to the DPRK. The different scenarios within the model cannot be distinguished, or produce a clear estimate of what the DPRK fissile material stockpiles are without more information on how the North Korean fissile material production complex operates.

The scenarios presented by the model are based on 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.

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